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LISTE DES ABRÉVIATIONS, SIGLES ET ACRONYMES

ABRÉVIATIONS

ER	électrorhéologique
SERDA	<i>Smart ER dynamic absorber</i>

SIGLES ET ACRONYMES

C_{ER}	coefficient non-linéaire d'amortissement en torsion (N.m.s/rad)
C_{eq}	coefficient d'amortissement équivalent (N.m.s/rad)
d	taille de particule (μm)
E	champ électrique (kV/mm)
E_0	champ électrique (V/mm) pour 'nombre de Mason'
G_0	module de cisaillement du matériau quand le matériau travaille sous le seuil d'écoulement et en petite déformation
G_1	module élastique en cisaillement (Pa)
G_2	module visqueux en cisaillement (Pa)
H	hauteur de cylindre intérieur (m)
J_1	moment d'inertie de masse du rotor (kg.m^2)
J_2	moment d'inertie de masse de l'absorbeur (kg.m^2)
K_1	la constante de rigidité en torsion (N.m/rad)
K_{ER}	rigidité complexe non- linéaire en torsion (N.m/rad)
K_{ER0}	valeur maximale de K_{ER} (N.m/rad)
K_{EReq}	K_{ER} équivalent (N.m/rad)
M	couple d'excitation (N.m)
M_{ER}	couple appliqué aux cylindres du système grâce à l'effet du fluide ER (N.m)
n	constante de Cross

m	constante non dimensionnelle pour le modèle de Bingham
R	rayon de cylindre extérieur du système (m)
R_0	rayon de cylindre intérieur du système (m)
t	constante de temps de Cross (s)
β	rapport de fréquence naturelle
δ	facteur de perte du matériau viscoélastique
$\tan \delta_e$	tangente de perte pour décrire la constante diélectrique complexe
ϵ_c	constante diélectrique du liquide
ϵ_p	constante diélectrique des particules
ϵ_0	constante diélectrique sous vide
ϵ'	partie réelle de permittivité diélectrique
ϵ''	partie imaginaire de permittivité diélectrique
ϵ_∞	permittivité à la fréquence infinie
ϵ_s	permittivité à la fréquence nulle
ϕ	concentration de particules en masse (%)
γ_y	déformation sous le seuil d'écoulement
$\dot{\gamma}$	vitesse de cisaillement (1/s)
$\dot{\gamma}_1, \dot{\gamma}_2$	vitesse de cisaillement critiques
η	viscosité dynamique (Pa.s)
η_c	viscosité du liquide (Pa.s)
η_0	viscosité à vitesse de cisaillement nulle
η_∞	viscosité à la vitesse de cisaillement infinie
μ	rapport du moment d'inertie de rotation

θ_1	déplacement angulaire du rotor (rad)
θ_2	déplacement angulaire de l'absorbeur (rad)
σ_{dc}	conductivité électrique (S/m)
ζ	taux d'amortissement
τ_0	fréquence de la relaxation (Hz)
τ	contrainte de cisaillement (Pa)
τ_{yB}	seuil d'écoulement dans le modèle de Bingham (Pa)
τ_{yQB}	seuil d'écoulement dans le modèle de Quasi-Bingham (Pa)
ξ	concentration volumique de surfactant (ppm)
ω	pulsation (rad/s)

LIST OF ABBREVIATIONS, SYMBOLS AND ACRONYMS

ABBREVIATIONS

ER	electrorheological
SERDA	Smart ER dynamic absorber

SYMBOLS AND ACRONYMS

C_{ER}	torsional nonlinear damping coefficient (N.m.s/rad)
C_{eq}	equivalent damping coefficient (N.m.s/rad)
d	particle size (μm)
E	electric field (kV/mm)
E_0	electric field (V/mm) for Mason number
G_0	shear modulus (Pa)
G_1	elastic shear modulus (Pa)
G_2	viscous shear modulus (Pa)
H	inner cylinder height (m)
J_1	rotational inertia of rotor (kg.m^2)
J_2	rotational inertia of absorber (kg.m^2)
K_1	torsional stiffness (N.m/rad)
K_{ER}	nonlinear torsional stiffness (N.m/rad)
K_{ER0}	maximum value of K_{ER} (N.m/rad)
K_{EReq}	equivalent K_{ER} (N.m/rad)
M	torque of excitation (N.m)
M_{ER}	applied torque on cylinders of system due to ER effect of fluid (N.m)
n	Cross constant

m	nondimensional constant for Bingham model
R	outer cylinder radius (m)
R_0	inner cylinder radius (m)
t	Cross time constant (s)
β	ratio of natural frequency
δ	loss factor
$\tan \delta_e$	loss factor or Loss tangent for complex dielectric constant
ϵ_c	dielectric constant of liquid
ϵ_p	dielectric constant of particle
ϵ_0	vacuum dielectric constant
ϵ'	real part of permittivity
ϵ''	imaginary part of permittivity
ϵ_∞	permittivity at infinity frequency
ϵ_s	permittivity under direct voltage
ϕ	particle concentration in weigh (%)
γ_y	yield strain
$\dot{\gamma}$	shear rate (1/s)
$\dot{\gamma}_1, \dot{\gamma}_2$	critical shear rate
η	dynamic viscosity (Pa.s)
η_c	viscosity of liquid (Pa.s)
η_0	viscosity at zero shear rate
η_∞	viscosity at infinity shear rate
μ	ratio of rotational inertia

θ_1	rotational angle of rotor (rad)
θ_2	rotational angle of absorber (rad)
σ_{dc}	electric conductivity (S/m)
ζ	damping ratio
τ_0	relaxation frequency (Hz)
τ	shear stress (Pa)
τ_{yB}	yield stress in Bingham Model (Pa)
τ_{yQB}	yield stress in Quasi-Bingham Model (Pa)
ξ	volume concentration of surfactant (ppm)
ω	pulsation (rad/s)

CHAPITRE 1

INTRODUCTION

Dans les deux dernières décennies, beaucoup de scientifiques, d'ingénieurs et d'inventeurs ont été fascinés par les fluides électrorhéologiques (ER). Grâce à leurs propriétés spécifiques telles que : réversibilité, réponse rapide, viscosité variable, etc, ces fluides peuvent être utilisés afin de contrôler les vibrations (Stanway, Sproston et al. 1996; Choi et Kim 2000) et l'amortissement (Thomas, Masounave et al. 1997; Sun, Thomas et al. 2006) au moyen des champs électriques. Ces systèmes ER peuvent être employés comme une interface entre les systèmes mécaniques et les systèmes électroniques afin de réaliser une procédure automatique de contrôle en temps réel. Certains systèmes industriels ont été développés en utilisant des fluides ER, tels que embrayages, freins, amortisseurs d'impacts et de vibration, notamment dans le transport (Figure 1.1: Sassi et al. 2003), etc.

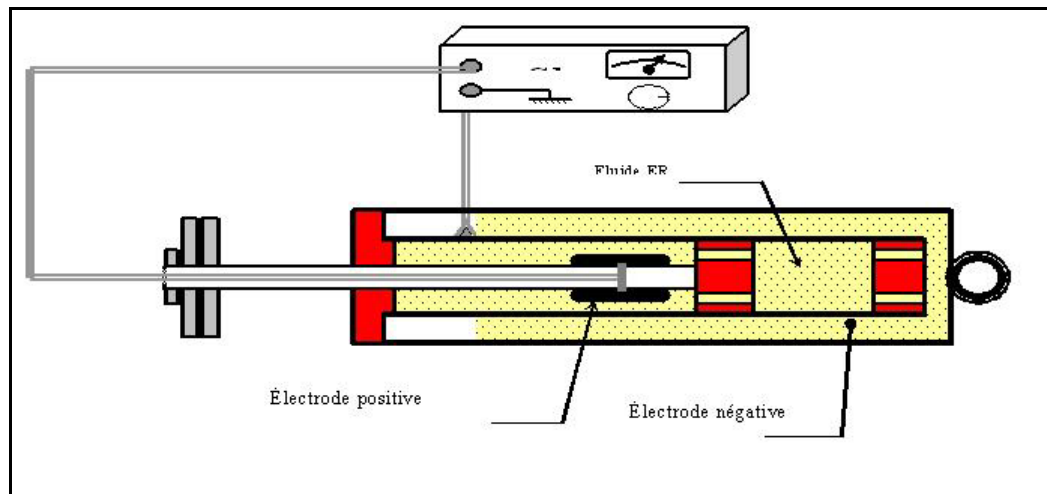


Figure 1.1 Amortisseur ER de véhicule.

Tirée de (Sassi, Chérif et al. 2003)

Cependant, il existe beaucoup de problèmes techniques à résoudre tels que la sédimentation des particules, l'effet de l'humidité, l'échauffement du fluide (Hosseini-Sianaki, Bullough et al. 1998), l'abrasion des électrodes et les arcs électriques, etc. qui ont tendance à limiter les

applications industrielles des fluides ER (Bullough 1995; Nakano et Koyama 1997). En outre, les appareils utilisant la technologie ER nécessitent l'application de hautes tensions, ce qui nécessite un équipement sophistiqué, entraîne des coûts élevés et pose des problèmes de sécurité. Les chercheurs tentent de développer des technologies de fabrication des fluides ER qui pourraient résoudre tous ces problèmes (Tao 1999; Bossis 2001), mais la réalisation est difficile, car les performances des fluides ER ne dépendent pas seulement du mélange liquide-particule, de la taille des particules, de la forme des particules (Qi et Wen 2002), du rapport de densité entre les particules et le liquide, de l'effet des surfactants (Lee, Chin et al. 1998), etc., mais aussi de nombreux autres facteurs, tels que la vitesse de cisaillement, le champ électrique, la fréquence du champ électrique (Boissy 1999; Kim et al. 2003; Lan et al. 2004), la concentration de particules (Gavin 1997; Lengálová, Pavlínek et al. 2003), la conception de mise en œuvre (Sassi, Chérif et al. 2003), etc.

Les applications des fluides ER sont à développer, mais certains problèmes ont tendance à empêcher leurs applications et leur commercialisation telles que :

- Les comportements rhéologiques des fluides ER sont très complexes et non-linéaires. Il n'existe pas actuellement de bon modèle pour décrire leurs propriétés;
- Certains problèmes techniques, tels que la sédimentation des particules, le réchauffement du fluide, l'effet de l'humidité, de l'abrasion et des arcs électriques provoquent la perte des propriétés, etc., et ont donc tendance à limiter les applications des fluides ER;
- Les appareils à fluides ER contrôlables ont besoin de haute tension ce qui pose des problèmes de sécurité.

1.1 Problématique de la recherche

Beaucoup de méthodes passives, semi actives ou actives pourraient être utilisées pour réduire les vibrations. Les méthodes passives peuvent jouer sur les masses, rigidité et amortissement d'un système mécaniques. Elles sont à la fois fiables, robustes et sécuritaires. Les méthodes actives en jouant sur les paramètres structurels tels que masse, rigidité et amortissement sont plus efficaces pour contrôler les vibrations, mais présentent un risque en cas de défaillance

du système actif. Les méthodes semi-actives en jouant principalement sur l'amortissement d'un système sont donc plus sécuritaires et présentent un compromis entre les méthodes passives et actives. Outre l'amortissement passif des structures par introduction de matériaux viscoélastiques (Thomas, Masounave et al. 1997), une méthode pratique pour réduire les vibrations consiste à introduire dans le système un absorbeur dynamique (Thomas and Laville 2005). Il est utilisé passivement, car ses paramètres physiques sont constants. De ce fait, la gamme efficace en fréquence de l'absorbeur dynamique se trouve réduite. Cette méthode est donc pratique pour des systèmes à vitesse constante, mais n'est pas viable pour des systèmes à vitesse variable. On pourrait alors augmenter l'amortissement passif de l'absorbeur, mais au détriment de sa performance. Ces méthodes de contrôle sont généralement utilisées en flexion, mais peu de méthodes existent pour atténuer les vibrations de rotors en torsion, puisque le système tourne. Les vibrations de rotors en torsion sont des phénomènes indésirables très difficiles à contrôler. Les matériaux intelligents pourraient être un outil intéressant pour augmenter la gamme de fréquences d'absorbeur dynamique de manière à pouvoir varier leurs propriétés. Dans cette étude, une application a été développée pour réduire les vibrations en torsion d'un rotor.

1.2 Objectifs de la recherche, originalité et méthodologie

L'objet principal de cette recherche consiste à développer un fluide ER, à étudier ses performances rhéologiques en faisant varier certains paramètres caractérisés (la concentration de particules, la taille des particules, les surfactants, le champ électrique et la vitesse de cisaillement), à développer un modèle adéquat pour modéliser le comportement dynamique de ces fluides afin, par la suite, de développer une application de contrôle des vibrations afin de valider ses performances et les modèles.

Le contrôle des fluides ER permet de faire varier activement la viscosité et par conséquent l'amortissement des structures, une approche semi-active a donc été choisie. Selon nos résultats, un amortisseur ou un absorbeur contenant un fluide ER permet de contrôler l'amortissement et la rigidité d'une structure (Thomas, Masounave et al. 1997; Sun, Thomas

et al. 2006). Les vibrations de rotors en torsion étant difficiles à contrôler, c'est donc l'application que nous avons choisie, puisque ce type de fluide le permet. À cette fin, nous visons à développer un nouveau type d'absorbeur dynamique semi-actif qui agira en torsion (type Houdaille) (Thomas et Laville 2005), afin d'augmenter la gamme utile en fréquence pour des systèmes à vitesse variable.

Nous avons axé nos travaux autour de trois articles de revue (inclus intégralement dans les chapitres 3, 4 et 5) et trois articles de conférence qui ont déjà été publiés (voir annexe 1). Étant donné que certains aspects de la revue de littérature sur fluides électrorhéologiques n'ont pas été abordés dans les articles, nous avons fait un résumé dans le chapitre 2.

Les objectifs spécifiques de l'étude visaient donc le contrôle semi-actif des vibrations de rotors en torsion par l'application des fluides électrorhéologiques. Pour arriver à ce but, les étapes de travail de notre projet ont été :

1. Développement et modélisation des fluides ER et établissement d'une équation de prédiction. Nous avons développé un nouveau fluide ER qui a été appelé ETSERF. Il est composé d'une suspension de poudres de diatomites dispersées dans l'huile de silicone avec le surfactant TWEEN80 (Polyethylene glycol sorbitan monooleate). Un plan d'expérience a été réalisé afin d'identifier statistiquement les paramètres significatifs qui contrôlent le comportement rhéologique du fluide (Sun et al. 2007). C'est un outil puissant pour comprendre et prédire les effets des facteurs les plus significatifs ainsi que l'effet des interactions de ces paramètres, sur le comportement rhéologique. Un nouveau modèle appelé Quasi-Bingham a été développé. Une relation quantitative entre la contrainte de cisaillement dynamique et les variables indépendantes a été développée. Cette relation est basée sur le modèle de Bingham. Elle donne une bonne explication des contributions de chaque paramètre indépendant sur la viscosité et le seuil d'écoulement. Un modèle empirique à 5 paramètres, nommé modèle de Quasi-Bingham, est proposé. Ce modèle peut être appliqué à tous les types de fluides ER qui possèdent un comportement rhéofluidifiant ou pseudoplastique. Il

permet de prédire plus précisément les influences des variables indépendantes sur la viscosité et le seuil d'écoulement. Les résultats obtenus par les deux modèles, Bingham et Quasi-Bingham, sont comparés avec les résultats expérimentaux. Cette étude est décrite dans deux articles de revue et un article de conférence:

- Sun Y., Thomas M. et Masounave J., 2009, « An experimental investigation of the dielectric properties of electrorheological fluids », a été publié dans la revue *Journal of Smart Materials and Structures (SMS)*, 18, 024004, 9 p. Dans cet article, les résultats d'observations expérimentales des propriétés diélectriques du nouveau fluide ER sont présentés.
- Sun Y, Thomas M. et Masounave J., 2009, « A Quasi-Bingham model for predicting Electrorheological fluid behaviour », a été soumis à la revue *Measurement Science and Technology (MST)*. L'objet principal de cet article est consacré à l'étude des performances d'un nouveau fluide ER et à la modélisation du fluide ER.
- Sun Y., Thomas M., et Masounave J., Juillet 2007, « Experimental investigation of dielectric properties on Electrorheological fluids », *International Conference on Smart Materials and Nanotechnology in Engineering (SMN2007)*, *Proceedings SPIE*, Vol 6423, 642334, Shanyi Du, Jinsong Leng et Anand K. Asundi éditeurs. Harbin Chine, 8p.

2. Modélisations des matériaux ER en fonctionnement dynamique afin de décrire l'amortissement et la rigidité en torsion du fluide ER quand le champ électrique est appliqué. Un modèle non linéaire est proposé, basé sur le modèle de Quasi-Bingham. Un modèle non-linéaire est proposé, basé sur le modèle de Quasi-Bingham afin de décrire la performance dynamique du fluide ER. Ces travaux sont décrits dans un article de conférence :

- Sun Y., Thomas M. et Masounave J., Octobre 2004, « Investigation of Dynamic Behavior of Electrorheological Fluids by Experimental Design », *Proceedings of the 7th Cansmart meeting, International workshop, Smart Materials and structures*, Montreal, pp 153-162.

3. Modélisation, simulation et conception d'un absorbeur dynamique électrorhéologique contrôlable à l'aide du fluide ER. Le fluide ER a été choisi pour être intégré à un absorbeur dynamique à cause de ses propriétés permettant notamment d'élargir la gamme de fréquences à contrôler. Un absorbeur dynamique contenant un fluide ER appelé « Smart ER dynamic absorber » (SERDA) est par conséquent développé afin de contrôler les vibrations en torsion d'un rotor. Cet absorbeur est contrôlable et particulièrement adapté pour des rotors opérant à vitesse variable. Ces travaux sont décrits dans un article de conférence :
 - Sun Y, Thomas M. and Masounave J., 2006, « Damping of rotor torsional vibrations with electrorheological fluids », *Proceedings of the 24th Seminar on machinery vibration*, Canadian Machinery Vibration Association, ISBN 2-921145-61-8, Montréal, pp. 344-369.
4. Conception et fabrication d'un banc d'essai afin d'évaluer l'efficacité d'absorbeurs ER dynamiques en torsion. L'analyse théorique et les simulations expérimentales de l'absorbeur SERDA ont été réalisées afin de comprendre l'effet d'un champ électrique sur l'amortissement et sur la rigidité en torsion.
5. Validation des modèles en faisant des mesures avec le système muni de l'absorbeur SERDA. Ces travaux sont décrits dans un article de revue. Dans cette étude, une simple stratégie de contrôle des vibrations 'on-off' a été choisie pour réduire les vibrations.
 - Sun Y et Thomas M., 2009, « Control of Rotor Torsional Vibrations by using an Electrorheological Fluid Dynamic Absorber », a été accepté par *Journal of Vibration and Control (JVC)*, 37 pages. Cet article se concentre principalement sur une application du nouveau fluide ER au contrôle semi-actif des vibrations de rotors.

CHAPITRE 2

REVUE DE LA LITTÉRATURE

2.1 Principe des fluides électrorhéologique (ER)

En 1949, Winslow remarqua une augmentation de la viscosité dynamique apparente en temps réel de certains fluides, dits fluides électrorhéologiques, quand ils sont soumis à un champ électrique. Le temps de réponse est de l'ordre de la milliseconde. Ce phénomène est appelé phénomène électrorhéologique, désigné par ER. Le comportement du fluide ER est très sensible au champ électrique, à l'état du fluide ER qui peut être modifié de liquide à quasi-solide (fortement visqueux). Le fluide ER retourne à l'état initial lorsque le champ électrique est coupé. Les fluides ER sont notamment caractérisés par une haute contrainte de cisaillement, une réponse rapide sous l'action d'un faible courant électrique. Leurs propriétés sont surtout sensibles à des facteurs tels que la vitesse de cisaillement, la fréquence du champ électrique, la composition du fluide, la température, l'humidité et l'addition d'additifs, etc. (Block and Kelly 1988; Stanway, Sproston et al. 1996; Choi SB, Bang JH et al. 2002).

2.1.1 Définitions d'un fluide électrorhéologique

La rhéologie peut être définie comme la science de l'écoulement et de la déformation de la matière. Elle étudie les réactions des matériaux aux forces extérieures. La rhéologie tient compte de l'histoire de l'échantillon : mode d'application de la force, rapide ou lente, état de la matière. L'électrorhéologie consiste à étudier la rhéologie de la matière lorsqu'elle est soumise à un champ électrique. Les fluides électrorhéologiques sont des fluides dont la viscosité apparente varie (augmente ou diminue) en temps réel (quelques millisecondes) quand ils sont soumis à un champ électrique élevé (Block et Kelly 1988).

2.1.2 Composition des fluides électrorhéologiques

Un fluide électrorhéologique (ER) est constitué d'une suspension des particules polarisables dispersées dans un liquide diélectrique (Block et Kelly 1988). Les particules solides sont souvent des matériaux inorganiques non-métalliques, organiques et polymériques semi-conducteurs (telles que silice, amidon, cacao, cellulose, poudre d'alumine, polymère, etc.). Le liquide support est souvent l'huile de polydimethylsiloxane (l'huile de silicone), l'huile minérale, le paraffine et l'huile d'hydrocarbure chloré, etc. (Block et Kelly 1988).

2.1.2.1 Les particules

La taille, la forme ainsi que la nature chimique des particules sont des caractéristiques dont on doit tenir compte (Halsey et C. 1993; Hao 2002) :

- Les tailles sont généralement comprises entre 0.1 et 100 μm . La taille minimale requise est mal définie. Les particules de faible dimension donnent lieu à des mouvements browniens qui entrent en compétition avec les forces électriques. Les particules de tailles plus grosses sédimentent facilement et entraînent des temps de réponse plus longs;
- La fraction volumique de particules est généralement comprise entre 0,05 et 0,5. Une fraction élevée favorise la fibrillation (formation de chaînes) et augmente la viscosité en l'absence de champ électrique. Il existe une concentration optimale qui donne une fluidité acceptable en l'absence de champ tout en ayant un effet électrorhéologique notable;
- La densité de particules et celle du liquide doivent être comparables pour éviter la sédimentation (Block et Kelly 1988). Ils concluent que les particules polymériques avec ou sans surfactants peuvent être utilisées pour contrôler la sédimentation des fluides ER.

Deux types de particules peuvent être considérés pour préparer des fluides ER: les particules polarisables intrinsèquement ou extrinsèquement (Jordan et Shaw 1991) :

- Polarisation extrinsèque: ce sont des particules hydrophiles qui ont besoin d'un activateur polaire pour fournir un effet électrorhéologique conséquent. Cet effet semble alors dépendre essentiellement de la polarisation interfaciale;
- Polarisation intrinsèque: ce type de particules peut être polarisé sans l'addition d'activateur polaire, ce qui augmente notablement la plage d'utilisation en température. Il peut se créer une polarisation interfaciale ou une polarisation dipolaire ou les deux en même temps.

2.1.2.2 Le liquide support

Une activité électrorhéologique peut être prévisible pour les systèmes biphasés dans lesquels il existe une différence substantielle entre les constantes diélectriques des phases. La phase continue est souvent une huile isolante. Une faible conductivité permet de minimiser les courants de fuite. Le fluide support doit posséder les autres caractéristiques suivantes:

- Un point d'ébullition élevé et de solidification basse;
- Une faible viscosité;
- Une haute densité pour empêcher la sédimentation de particules;
- Une grande stabilité chimique;
- Une hydrophobicité évidente;
- Une toxicité basse.

La densité du liquide joue également un rôle sur la stabilité de la dispersion. Une valeur élevée limite la sédimentation, mais augmente la viscosité sans champ électrique; il faut donc trouver un compromis (Hao 2002).

2.1.2.3 L'activateur polaire

Le plus souvent, on utilise de l'eau, mais d'autres liquides, tels que les alcools, éthanol, diéthylamine et les amines légères peuvent également tenir ce rôle. Les concentrations habituelles varient entre 5 et 10 % (en masse) de la phase dispersée (pour l'eau). Il joue un rôle déterminant dans l'effet électrorhéologique (Burchill 1991). Dès que les particules du

fluide ER absorbent une petite quantité d'eau (Uejima 1972; Otsubo, Sekine et al. 1991; Otsubo, Sekine et al. 1992) ou d'autre activateur polaire (alcool, éthylène glycol, diméthylformamide, etc.) (Block and Kelly 1988), l'effet ER de ce fluide est nettement modifié pour beaucoup de matériaux, à l'exception des suspensions fabriquées avec certains polymères dont la surface est peu sensible aux surfactants (Pavlinek, Quadrat et al. 1999). Il est observé que l'eau absorbée peut augmenter la performance ER du fluide en comparaison avec des particules sèches (anhydres).

Des particules hydrophiles en suspension dans une huile hydrophobe donnent lieu à des effets électrorhéologiques avec faibles quantités d'eau. Souvent les particules ne présentent pas d'effet ER en l'absence d'eau. Dans ce cas, l'effet de l'eau est considéré comme un pont électrique entre les particules hydrophiles. De fait, l'énergie de surface élevée de l'eau peut laisser supposer qu'elle joue le rôle d'adhésif. Lors de l'application du champ électrique, les deux phénomènes principaux peuvent être rencontrés, soit l'électrophorèse, soit l'électro-osmose. La technique de l'électrophorèse est fondée sur le déplacement d'ions (molécules ayant perdu leur neutralité électrique) sous l'action d'un champ électrique. L'électro-osmose est un phénomène qui résulte du mouvement d'un fluide (qui peut être l'eau désionisée ou un électrolyte ou un fluide organique) lorsque l'on applique un champ électrique tangentiel dans la couche diffuse. Si une électro-osmose interne est le mécanisme de base de l'effet électrorhéologique, elle peut accroître la différence de charge entre la matrice solide et l'eau augmente l'effet électrorhéologique. L'utilisation de l'eau pose cependant certains problèmes, notamment en ce qui concerne la gamme de température d'utilisation. En effet, lors du chauffage, l'eau s'évapore et la modification de la composition du fluide entraîne une modification des performances. En dessous de 0 °C, certains problèmes sont également à redouter, par exemple la congélation de l'eau. De plus, l'eau peut conduire à de la corrosion et à des phénomènes de rupture diélectrique et elle est à l'origine d'une consommation électrique plus importante. Les fluides anhydres possédant une activité électrorhéologique sont rares et sont le plus souvent décrits au travers de brevets. Il a été récemment démontré que les particules semi-conductrices, tel que le phtalocyanine de cuivre possède des propriétés électrorhéologiques en l'absence d'une troisième phase (les surfactants, l'eau, les

activateurs polaires). Ces fluides "secs" se présentent une avancée considérable en autorisant le développement de technologies électrorhéologiques à basses et hautes températures (Jordan et Shaw 1991). Si l'eau joue un rôle central, la quantité d'eau additionnée peut également être déterminante (Jordan et Shaw 1991). L'addition d'une trop grande quantité d'eau peut conduire à l'effet inverse de celui désiré, l'eau joue alors le rôle de lubrifiant en enrobant toute la surface de la particule. En ce qui concerne l'adsorption des molécules d'eau, il convient de bien dissocier la mobilité et la disponibilité (Jordan et Shaw 1991). Si les sites d'absorption sur le solide sont proches et partiellement occupés, le transfert des molécules d'eau d'un site à l'autre réclamera peu d'énergie. En revanche, enlever la totalité de l'eau absorbée par les particules, réclamera une énergie beaucoup plus grande. C'est cette différence qui permet à des fluides électrorhéologiques de fonctionner en dehors de la gamme 0-100°C ce qui occasionne certaines difficultés quant à la mesure de la quantité d'eau adsorbée. L'approche par "pont aqueux" est difficilement modélisable, car l'effet de l'eau est compliqué et il n'existe pas de modèle parfait pour le décrire.

La couche d'eau absorbée sur la particule, la présence d'eau dans les particules, génère des dipôles qui freinent le mouvement des électrodes. La présence d'eau peut entraîner donc une augmentation des forces électrostatiques qui augmente la force ER. En ne tenant compte que des interactions électrostatiques entre particules, la force mesurée due à l'effet électrorhéologique est souvent supérieure à celle calculée (Jordan et Shaw 1991). Cependant, le modèle "pont aqueux" s'accorde bien avec les observations lorsque les forces hydrodynamiques et les forces de polarisation sont les seules à posséder une contribution notable (See, Tamura et al. 1993; Pavlinek, Quadrat et al. 1999; Zheng, Winter et al. 2005).

2.1.2.4 Effet des surfactants

Un des problèmes majeurs dans l'utilisation des fluides électrorhéologiques est la sédimentation. Pour éviter cette difficulté, on peut ajouter des surfactants (savons, détergents) qui auront pour rôle de tenir les particules en suspension dans le fluide. Les surfactants sont souvent utilisés pour promouvoir la stabilité colloïdale, ce qui est nécessaire pour maintenir

les particules de manière irréversible de floculation, et pour contrôler les propriétés rhéologiques en l'absence du champ électrique. Les surfactants sont également utilisés pour activer les suspensions ER. Certaines suspensions présentent peu ou pas de comportement ER sauf si une petite quantité d'eau ou de surfactant est ajoutée. L'utilisation de surfactants entraîne parfois une perte de l'effet électrorhéologique. Mais les surfactants non-ioniques tels Span20, Span80 et Span85 sont choisis pour stabiliser des suspensions en évitant la réaggrégation des particules puisqu'ils sont plus stables chimiquement et électrostatiquement. Des surfactants non-ioniques permettent une stabilisation stérique qui consiste à adsorber une couche protectrice en surface des particules créant ainsi une barrière stérique à l'aggrégation, car la molécule de ce type de surfactant ne comporte aucune charge (Storrie et Madden 1990; Deshpande 1997; Lee, Chin et al. 1998).

2.1.3 Comportement des fluides ER

Sous l'influence d'un champ électrique extérieur, les particules du fluide ER sont polarisées. L'effet ER est le résultat de forces dues à la polarisation. Les dipôles tendent à s'orienter en suivant le vecteur du champ, et s'attirent les unes les autres. L'interaction électrostatique entre les dipôles crée des agglomérats de particules qui s'alignent en suivant la direction du champ électrique. Les interactions dipôle-dipôle génèrent donc des structures de chaînes dans la direction du champ (Figure 2.1). De ce fait, la viscosité apparente augmente, particulièrement à basse vitesse de cisaillement, et donc les propriétés rhéologiques du fluide sont modifiées. Les chaînes créent une résistance au mouvement, au cisaillement ou à la compression.

L'action hydrodynamique des chaînes est plus sensible lorsque les chaînes se créent. Les chaînes de particules sont rompues à haute vitesse de cisaillement et ont de la difficulté à se reformer à plus haute vitesse de cisaillement, qui est souvent plus grande que la vitesse de reformation, appelée temps de relaxation. Par conséquent, la viscosité apparente diminue au fur et mesure que la vitesse de cisaillement augmente jusqu'à ce qu'elle s'approche de la valeur obtenue l'absence d'un champ électrique.

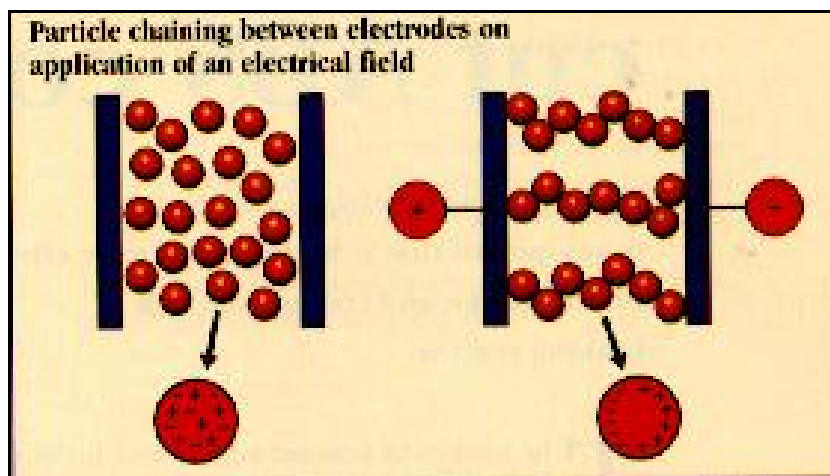


Figure 2.1 Formation des chaînes de particules.

Tirée de (Parthasarathy et J.Kingenberg 1996)

La viscosité apparente du fluide ER croît ou décroît lorsqu'un champ électrique est appliqué. L'effet électrorhéologique, qui est réversible, est établi en quelques dizaines de millisecondes à plusieurs dizaines de minutes, selon la composition du fluide. L'effet de transition d'un état liquide à un état quasi-solide est réversible, ce qui permet de développer des applications en contrôle.

2.1.4 Propriétés diélectriques des fluides ER

Beaucoup d'études qui présentent des calculs théoriques ou des simulations expérimentales ont été publiées récemment, basées sur des modèles diélectriques ou des modèles de conduction (Gast et Zukoski 1989; Conrad et Sprecher 1991; See et Doi 1992; Tamura et Doi 1992; Tao, Jiang et al. 1995; Ma, Wen et al. 1996; Davis 1997; Hao 2002). Selon la théorie de la polarisation de concentration (aussi appelé « Bulk polarisation » de Marshall, Zukoski et al. 1989), la polarisabilité des particules dépend de la permittivité du matériau dispersé, et aussi de l'état de la surface des particules. Cette dernière peut jouer un rôle très important pour les propriétés ER. Tenant compte de la limite de température, de l'usure de l'appareil, de l'évaporation de l'eau et de l'instabilité de la dispersion, certains fluides ER anhydres ont été développés et surtout étudiés du point de vue de leurs propriétés diélectriques (Cho, Choi et

al. 2004; Sung, Park et al. 2005; Hong et Choi 2007). La conductivité et la permittivité gouvernent la performance ER (Atten, Foulc et al. 2002). Certaines études montrent que le seuil d'écoulement ne change pas de façon linéaire avec la permittivité. Différentes préparations, en tenant compte par exemple de la température de déshydratation, entraînent des changements des propriétés ER puisque la conductivité du fluide ER est différente. La conductivité est aussi importante que la permittivité (Hao 1998). Étant donné que les composites organiques ou inorganiques possèdent des avantages qui peuvent conduire à la combinaison des propriétés de chaque matériau du composite, les composites de PANI/TiO₂ (Polyaniline et titanium dioxide) qui sont synthétisés par une polymérisation oxydante ont été étudiés dans les années récentes. L'étude de Sung et al indique que les particules de PANI/TiO₂ présentent une polarisation plus haute que celle des particules de PANI. Leur relaxation est aussi plus rapide. Les composites de PANI/ TiO₂ donnent une meilleure performance ER due à la haute polarisation. La rapidité de la relaxation est proportionnelle à la concentration de TiO₂. Cette rapidité pourrait augmenter la force électrostatique qui crée la force de cisaillement hydrodynamique. La performance ER du point de vue du comportement au cisaillement est donc nettement améliorée. Mais il existe une concentration critique de TiO₂ dans le composite de PANI/TiO₂ (Sung, Lee et al. 2005).

Un système hétérogène peut contenir quatre types de polarisation tels que : polarisation électronique, atomique, dipolaire et interfaciale dite de Maxwell-Wagner, on doit déterminer l'effet prédominant sur l'efficacité ER. Les propriétés diélectriques des composites ETSERF ont été observées expérimentalement et à partir des résultats, le type de polarisation dominant a été déterminé. Les performances de différents fluides ER ont été comparées. Les relations entre la permittivité et le temps de la relaxation du fluide ETSERF avec la taille des particules, la concentration de particules, l'humidité, l'addition de surfactant ont été étudiées expérimentalement. En particulier, l'influence du temps de relaxation sur l'effet ER a été analysée en observant le vieillissement du fluide ER.

2.1.5 Types des fluides ER

En général, les fluides ER sont classés en deux groupes : les suspensions hétérogènes, et homogènes. La plupart des fluides ER sont des suspensions hétérogènes sont composées de particules polarisables solides en suspension dans des fluides non polarisables. La figure 2.2 montre la classification des fluides ER (Hao 2002).

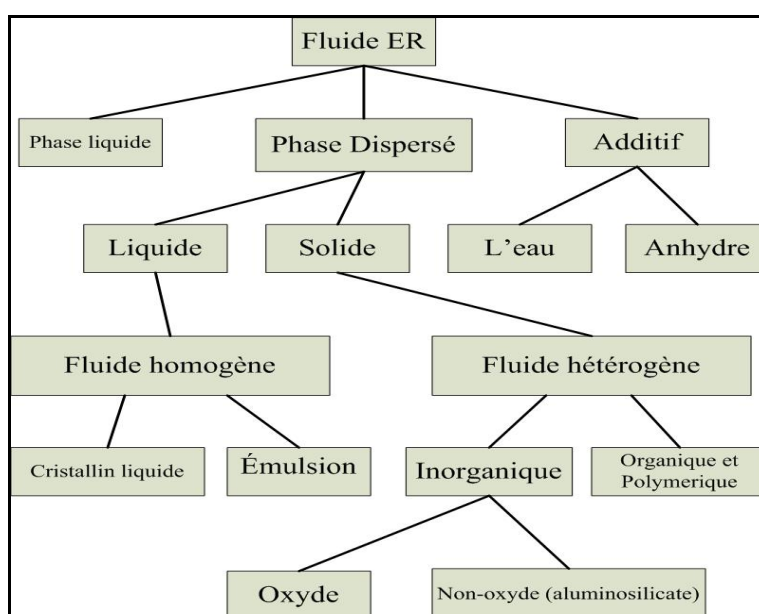


Figure 2.2 Classification de matériaux ER.

Tirée de Hao (2002)

Certains fluides ER sont composés d'émulsions, ils sont classés dans la catégorie des suspensions homogènes. Les fluides ER homogènes ont été développés au début les années 1990, dont les fluides LC («Low molecular liquid crystalline materials») qui sont étudiés comme les fluides ER (Inoue et Maniwa 1992; Yang et Shine 1992; Negita 1996; Tajiri, Ohta et al. 1997; Yao et Jamieson 1997). L'émulsion de l'huile de paraffine chlorée dans le l'huile de silicone (Pan et McKinley 1997) et l'émulsion de glycol polymérique dans le l'huile de silicone (Kimura, Aikawa et al. 1998) présentent un effet ER. Le mécanisme de la réponse rhéologique pour un système d'émulsion de l'huile-dans-l'huile a été étudié par Ha (Ha et

Yang 2000). Il est possible que le fluide homogène puisse être prometteur. Certains problèmes nuisent par contre à leurs applications, comme par exemple la haute viscosité en l'absence du champ électrique (alors qu'on désire une faible valeur pour bénéficier de l'effet réversible) et la stabilisation de l'émulsion, etc. (Hao 2002).

Les fluides ER sont classés en fluide positif et négatif. Les plupart des fluides ER présentent un effet positif, c'est-à-dire que la viscosité apparente du fluide ER croît quand un champ électrique est appliqué. Cependant, un phénomène opposé a été rapporté par Boissy en 1995 (Boissy, Atten et al. 1995). Ils ont observé une diminution de la viscosité apparente d'un fluide ER composé de particules de polyméthylmethacrylate (PMMA) dispersées dans l'huile de silicone, lorsqu'un champ électrique est appliqué. Ce phénomène est opposé à l'effet ER dont on parle souvent. Dans les années suivantes, certains fluides négatifs ont été développés, le couple téflon/l'huile de silicone (Wu et Conrad 1997) et hydroxyde magnésium/l'huile de silicone (Trlica, Quadrat et al. 1996), etc. Le processus d'électrophorèse présente souvent un effet négatif. L'effet ER négatif pourrait donc être utilisé dans une application industrielle de contrôle des vibrations (Bouزيدane et Thomas 2007).

2.1.6 Mélanges usuels

Un fluide ER performant devrait posséder les propriétés suivantes :

1. Un changement remarquable de la contrainte de cisaillement dès que le champ électrique est appliqué;
2. Une réponse rapide;
3. Une basse densité de courant de fuite dans le fluide ER;
4. Une grande gamme de température de travail;
5. Une grande stabilité chimique et physique.

Pour atteindre les objectifs ci-dessus, de nombreux fluides ER ont été développés depuis les années 50. Nous pouvons trouver certaines compositions de ce genre de fluides ER dans le tableau 2.1.

Les oxydes métalliques et les matériaux céramiques frittés de plusieurs oxydes peuvent fournir un bon effet ER. Les fluides ER inorganiques non-oxydes ont été aussi étudiés à la fin des années 1980 et au début des années 1990. Les résultats de ces travaux ont montré que ce type de fluide déshydraté possède un très fort effet ER que l'eau pourrait encore augmenter. On peut citer les aluminosilicates et les matériaux de la famille des zéolites. Certains fluides ER non-oxydés inorganiques sont présentés dans le tableau 2.1. Étant donné que la conductivité des fluides ER non-oxydés inorganiques est très haute, particulièrement à haute température, et que la densité de particules est souvent plus élevée que celle des liquides, les suspensions ne sont pas stables. D'autre part, les particules sont très dures et donc usent rapidement les équipements.

Les matériaux organiques et polymériques ont donc été préférés par les chercheurs surtout dans les dernières années. Certains de ces fluides sont montrés dans le tableau 2.1. En général l'effet ER des fluides organiques est faible en comparaison de celui des matériaux non-oxydés inorganiques, malgré que les fluides organiques procèdent beaucoup d'avantages. Les fluides ER homogènes ont été étudiés, surtout parce qu'ils sont peu sensibles à la sédimentation. Certains fluides donnent un effet ER négatif, ce qui peut être très utile dans certains cas. Par exemple, Bouzidane et Thomas (2007) ont besoin de la diminution de la viscosité du lubrifiant afin de diminuer l'amortissement du palier opérant à très haute vitesse afin de réduire la vibration, en utilisant un négatif fluide ER. Cependant, ces types de fluides ne donnent pas un effet ER très fort, et les deux phases se séparent très facilement. La viscosité pour un champ électrique nul est très élevée, ce qui, en général, n'est pas recherché. Dans tableau 2.1, nous pouvons trouver quelques informations sur les fluides ER homogènes (Hao 2002).

Tableau 2.1 Compositions des fluides ER

Types de particules	Fluide support	Additif	Référence
Fluides ER			
Piézoélectrique céramique	huile minérale	eau ou glycérol oléates	(Petrzhik, Chertkova et al. 1980)
Oxyde de fer (II/III)	pétrole ou dibutyl sébaçate	eau ou surfactant	(Winslow 1953)
Silice	Kérosène ou dibutyl sébaçate, huile minérale, huile de silicone	eau et savon eau et glycérol oléates	(Winslow 1953; Winslow 1962)
Oxyde d'étain (II)	pétrole	eau ou surfactant	(Winslow 1953)
Dioxyde de titane	huile minérale ou p-xylène ou polyphenylmethysiloxane	eau et glycérol oléates	(Petrzhik, Chertkova et al. 1980)
Al ₂ O ₃ , Cu ₂ O, ZnO, La ₂ O ₃ , ZrO ₂ , Ta ₂ O ₃ , MnO ₂ , CoO, Nb ₂ O ₃ , etc.	huile minérale	Polybutylsuccimide	(Kanbara et Tomizawa 1990)
Aluminosilicate (Si/Al ratio de 8 :1 à 175 :1)	huile de silicone ou hydrocarbure	Surfactant	(Gillies, Sutcliffe et al. 1989)
Cristalline zéolite (M _(x/n) [AlO ₂] _x (SiO ₂) _y].wH ₂ O M est cation métal	huile de silicone ou haute constante diélectrique hydrocarbure		(Filisko et Armstrong 1989)
Zéolite	huile de silicone ou hydrocarbure		(Filisko et Armstrong 1988)
Perles de Micro-verre	huile de transformateur		(Bytt 1987)
Aluminosilicate avec 1-25% eau cristallisé, Si/Al ratio de 0.15 à 0.80	huile de silicone	Polyhydroxylsiloxane	(Goossens et Oppermann 1987)
Silice, silice-alumia	huile minérale, polyalkylene huile minérale Paraffine Polyphenyl, phosphorique acide ester.	Sulfonates Phénates Phosphonates, succinique acide	(Tomizawa, Kanbara et al. 1989)
LiN ₂ H ₅ SO ₄	huile de silicone	Polymère noir	(Carlson 1988)
BN, AlN, B ₄ C	huile de silicone	Succimide	(Kanbara et Tomizawa 1990)
Acetamide modified nanometer titanium oxide	huile de silicone		(Zhao 2006)
Fluides ER organiques et polymériques			
Polymère acene-quinone radicals	Hydrocarbure Chloriné		(Block et Kelley 1987)
Polyvinylsilane crosslinked Matériaux cellulosiques	huile de silicone fluorinate huile de transformateur, huile végétale	Électrolytes eau ou autre électrolytes	(Uejima 1972; Podszum, Bloodworth et al. 1996)
Polyphenyl Polyvinylideneshalides	huile de mixture basée carbone	Hydroxyl aromatique composé	(Pialet 1996)
Polypyrroles	huile de transformateur, huile végétale, paraffine chloré, etc.		(Bryant, Lal et al. 1995)
Polyanilines	huile silicone		(Gow et Zukoski 1990; Pialet, Bryant et al. 1997)
Polymère acene-quinone radicals	Hydrocarbure Chloriné		(Block et Kelley 1987)
Polyvinylsilane crosslinked Matériaux cellulosiques	huile de silicone fluorinate huile de transformateur, huile végétale	Électrolytes eau ou autre électrolytes	(Uejima 1972; Podszum, Bloodworth et al. 1996)

Tableau 2.1 Compositions des fluides ER (suite)

Types de particules	Fluide support	Additif	Référence
Fluides ER organiques et polymériques			
Polyphenyl Polyvinylideneshalides	huile de mixture basée carbone	Hydroxyl aromatique composé	(Pialet 1996)
Polypyrroles	huile de transformateur, huile végétale, paraffine chloré, etc.		(Bryant, Lal et al. 1995)
Polyanilines	huile silicone		(Gow et Zukoski 1990; Pialet, Bryant et al. 1997)
Matériaux de teintures ioniques	huile minérale, huile de silicone, huile blanche, etc.	Molécule contenu hydroxyle carboxyle	(Carlson, Weiss et al. 1993)
Carboxylmethyl de sodium Dextrane	Polychlorinated biphenyls or o- dichlorobenzene, etc.	Sorbitan monooleate	(Stangroom 1980)
Polymethacrylic acide cross linked avec divinylbenzene	Hydrocarbures	eau	(Stangroom 1980)
Amidon	huile minérale, huile de transformateur, huile hydrocarbure	eau	(Winslow 1947; Westhaver 1976)
Oxyde de polyacrylonitrile	huile de silicone	eau	(Xu et Liang 1991)
Carbonated aromatic sulfonic acid or a salt	huile de fluorosilicone ou autre l'huile de silicone modifiée		(Endo 1999)
Silicon dioxide- water polyurethane nanometer	Dimethicone		(ZHU 2007)
Fluides ER homogènes			
Savon d'aluminium	huile minérale, huile de silicone ou polyalpha-olefine, etc.	2,6-Ditertbutyl	(Prick, Grasshoff et al. 1998)
Poly (γ -glutamate)	Ketone cyclique		(Haji, Sasaki et al. 1997)
Poly (n-hexyl isocyanate)	<i>p</i> -Xylene		(Yang et Shine 1992)
LC polysiloxanes	huile de silicone		(Yao et Jamieson 1997)
LC polysiloxanes	4'-(Pentyloxy)-4-bipheny carbonitrile		(Yao et Jamieson 1997)
4-n-Pentyl-4'-cyanobiphenyl			(Negita 1996)
Émulsion de paraffine chlorée/l'huile de silicone			(Pen and McKinley 1997)
Émulsion de polypropylene urethane-modifié /huile de silicone			(Kimura, Aikawa et al. 1998)
Émulsion de l'huile de roulette/huile de silicone			(Ha et Yang 2000)

2.2 Les modèles rhéologiques du fluides ER

Plusieurs modèles ont été proposés afin d'expliquer le phénomène ER. Dans cette thèse, nous nous sommes concentrés sur les mécanismes physiques qui expliquent les propriétés mécaniques macroscopiques. Quelques modèles connus, résumés dans l'article de M. Parthasarathy et al (Parthasarathy et J.Kingenberg 1996), seront utilisés, tels que le modèle de Bingham, le modèle de Casson, le modèle de la perte diélectrique (Hao 2002) et le modèle viscoélastique (Kamath et Wereley 1997).

2.2.1 Nombre de Mason Mn

Le nombre de Mason Mn a été proposé par Marshall et al (Marshall, Zukoski et al. 1989) pour proposer une relation entre la force électrostatique et la force mécanique. L'importance des interactions des particules a été déterminée par Marshall et al (Marshall, Zukoski et al. 1989). Ces auteurs ont proposé de s'appuyer sur la théorie du Nombre de Mason Mn afin de décrire cet effet. Le nombre de Mason (Mn) est le rapport entre les amplitudes des forces hydrodynamiques et celles électrostatiques. Il est aussi possible de décrire l'évolution de la microstructure et des propriétés rhéologiques. Dans l'expression de Mn (équation 2.1), la force hydrodynamique est au numérateur, et la force électrostatique au dénominateur.

$$Mn = \frac{\eta_c \dot{\gamma}}{2\epsilon_0 \epsilon_c \beta^2 E_0^2} \quad (2.1)$$

avec $\beta = (\alpha - 1)/(\alpha + 2)$ (2.2)

et $\alpha = \epsilon_p / \epsilon_c$ (2.3)

$$\frac{\eta}{\eta_\infty} = \frac{Mn^*}{Mn} + 1 \quad (\text{pour } Mn > 0) \quad (2.4)$$

Le nombre de Mason peut être interprété comme une vitesse de cisaillement non-dimensionnelle. Selon cette équation, on pourrait faire une analyse quantitative de la rhéologie du fluide ER en combinant les modèles développés. Mn^* est une constante de matériau.

2.2.2 Modèle de Bingham

L'hypothèse de Newton est valable pour de nombreux fluides, comme par exemple l'air et l'eau, mais la plupart de fluides doivent supporter une certaine contrainte de cisaillement (seuil d'écoulement) avant de commencer à s'écouler. Cette catégorie de fluides est dénommée fluides de Bingham. Pour expliquer les propriétés mécaniques des fluides ER, le modèle de Bingham est certainement le plus utilisé (Park et Park 2001).

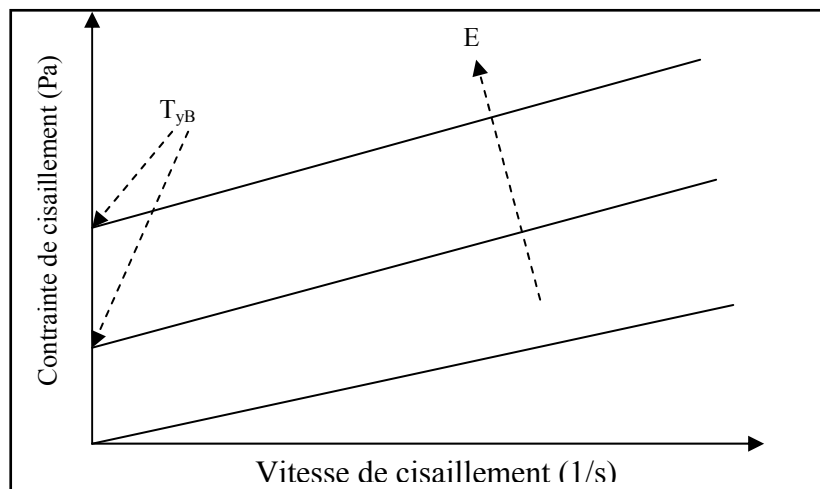


Figure 2.3 Rhéogramme d'un fluide de Bingham.

L'équation rhéologique des liquides de Bingham est :

$$\tau = \tau_{yB} + \eta \dot{\gamma}^m \quad (2.5)$$

où τ est la contrainte de cisaillement; τ_{yB} est le seuil d'écoulement; $\dot{\gamma}$ est la vitesse de cisaillement; m est un paramètre de puissance pour la vitesse de cisaillement, quand $m=1$, η est la viscosité, appelée parfois viscosité plastique. Le rhéogramme d'un fluide de Bingham est une droite ne passant pas par l'origine donc qui présente un seuil d'écoulement (figure 2.3).

2.2.3 Modèle de Casson

Certains résultats montrent que la relation entre la contrainte de cisaillement et la vitesse de cisaillement ne peut pas être décrite parfaitement par le modèle de Bingham. Parfois, la transition est graduelle dans les zones où la vitesse de cisaillement est ou très faible ou très grande, comme dans le cas des observations de Marshall et al. (Marshall, Zukoski et al. 1989). Bonnecaze et Brady (Bonnecaze et Brady 1992) ont suggéré qu'un modèle de Bingham-modifié avec une viscosité plastique qui dépend de Mn peut être utilisé pour décrire ce phénomène. Melrose et Heyes (Melrose et Heyes 1993) ont montré que le modèle de Casson est mieux adapté pour représenter leurs données expérimentales. Le comportement non-Bingham est associé à une rupture graduelle des structures qui est produite par le champ électrique (Marshall, Zukoski et al. 1989; Bonnecaze et Brady 1992; Martin, Odinek et al. 1992). Ce phénomène est observé expérimentalement (Jordan et Shaw 1989; Klingenberg et Zukoski 1990). L'équation de Casson est décrite par :

$$\tau^{1/2} = \tau_{yB}^{1/2} + (\eta\dot{\gamma})^{1/2} \quad (2.6)$$

2.2.4 Modèle de Cross

Le succès du modèle de Bingham-modifié vérifie la plupart des effets rhéologiques produits par le champ électrique pour de faibles vitesses de cisaillement (Parthasarathy et J.Klingenberg 1996). Beaucoup d'efforts pour la modélisation du fluide ER à basse vitesse, tels que les modèles de Casson et de Cross, ont été couronnés de succès. Dans l'article de W. Goodwin et al (Goodwin, Markham et al. 1997), plusieurs modèles ont été proposés pour

bien décrire l'effet ER. Ils ont observé que, lorsque la conductivité des particules est diminuée, l'effet ER est aussi diminué, et qu'un changement significatif du comportement de plastique à pseudoplastique, se produit quand la conductivité du fluide ER diminue. Cela implique que les équations simples constitutives de Bingham ou de Casson ne sont pas complètement adéquates pour décrire la réponse ER. Néanmoins, l'équation de Cross donne une bonne corrélation avec les données expérimentales, malgré que cette équation ne procède pas de terme de seuil d'écoulement (Goodwin, Markham et al. 1997). L'équation de Cross s'écrit:

$$\tau = \eta_{\infty} \dot{\gamma} + (\eta_0 - \eta_{\infty}) \frac{\dot{\gamma}}{1 + (t\dot{\gamma})^n} \quad (2.7)$$

où τ est la contrainte de cisaillement (Pa), $\dot{\gamma}$ est la vitesse de cisaillement (1/s), η_0 est la viscosité pour la vitesse zéro, η_{∞} est la viscosité à la vitesse infinie avec la même définition de η qui apparaît dans l'équation de Bingham (2.5). Les paramètres n et t sont caractéristiques du fluide ER. La constante " n " est connu comme la " constante de Cross". Cross a suggéré que $n \approx 1$ pour un système monodispersé et diminue à $2/3$ avec un système polydispersité. C'est un paramètre nondimensionnel qui dépend de la viscosité du fluide. Le paramètre " t " est défini comme une constante de temps.

CHAPITRE 3

ARTICLE #1 «A QUASI-BINGHAM MODEL FOR PREDICTING ELECTORRHEOLOGICAL FLUID BEHAVIOUR»

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Résumé

L'objet principal de cet article est consacré au développement d'un nouveau fluide électrorhéologique (ER), appelé *ETSERF* et à l'étude de ses caractéristiques rhéologiques. Le nouveau fluide ER est composé d'une suspension de poudres de diatomées dispersées dans l'huile de silicone avec le surfactant TWEEN80 (Polyethylene glycol sorbitan monooleate). Ce fluide ER appartient à la classe des fluides contrôlables (*smart materials*), dont le comportement rhéologique peut être commandé par l'application d'un champ électrique. Ces fluides peuvent être employés dans le domaine du contrôle, mais beaucoup de problèmes techniques sont à surmonter pour les appliquer convenablement. La méthode des plans d'expériences a été choisie. Le banc d'essai est décrit à l'annexe 1. Dans cet article, nous nous sommes concentrés sur les effets du champ électrique, de la vitesse de cisaillement, de la concentration de particules, de la taille des particules et du surfactant en lien avec la contrainte de cisaillement de ce nouveau fluide. Cette méthode est particulièrement efficace quand les interactions entre divers paramètres indépendants sont recherchées. C'est donc un outil très puissant pour comprendre et prédire les effets de paramètres indépendants sur les comportements rhéologiques. Pour bien décrire le comportement du fluide ER, deux modèles empiriques sont proposés basés sur les résultats d'une analyse de variance (ANOVA). Basée sur modèle de Bingham, une relation quantitative entre la contrainte de cisaillement et les variables indépendantes est développée.

Cette relation fournit une explication des contributions de chaque paramètre indépendant sur la viscosité et le seuil d'écoulement. Un autre modèle empirique, appelé modèle de Quasi-Bingham, a été proposé pour décrire le fluide ER. C'est une équation universelle qui peut être employée pour tous les fluides ER qui possèdent un comportement rhéofluidifiant. Les paramètres de cette équation peuvent être obtenus par régression. Ce modèle empirique permet de prédire l'influence des facteurs sur le seuil de cisaillement et la viscosité. Les résultats obtenus par les deux modèles sont proches des résultats expérimentaux. Cet article a été soumis à 'Measurement science and Technology (MST)', et est présenté intégralement dans la section suivante.

Abstract

This paper presents experimental research on the behaviour of a new electrorheological fluid (ETSERF). The ETSERF is a suspension based on diatomite powders dispersed in silicon oil with a surfactant. A design of experiments is conducted to investigate the effects of electric field strength, particle concentration, surfactant percentage, particle size and shear rate on the efficiency of electro-rheological fluids. The influence of the interactions on shear stresses is analyzed by varying all the combinations of the independent variables. The dielectric properties of the ETSERF are investigated in order to explain the interactions between these independent variables. Furthermore, a quantitative relationship between the dynamic shear stresses and the independent variables is developed. The relationship provides a very useful explanation for the contributions of each independent variable to the viscosity and yield stress. A new empirical model is proposed to explain the rheological behaviour of the ER fluids with a shear-thinning behaviour.

Key words: Electrorheological fluid, experimental design, ANOVA, Quasi-Bingham model, dielectric properties.

3.1 Introduction

An electrorheological (ER) fluid consists of a suspension of micron-sized polarizable particles (such as silica gel, cornstarch, cacao, cellulose, alumina powder, polymer, etc.) dispersed in a dielectric liquid (such as silicone oil, olive oil, mineral oil, etc.) [1]. When ER fluids are subjected to an electric field, their rheological properties are changed due to the formation of particle chains between the electrodes. These chains cause a resistance to flow (flow mode), to the shearing motion of electrodes (shear mode) or to squeeze (squeeze mode). ER fluids can be changed from a liquid to a quasi-solid state under an electric field, and can return to their initial state when the electric field is withdrawn, with the effect being reversible in milliseconds. The ER phenomenon was first described by Winslow in 1949 [2]. ER fluids are notably characterized by a high shear stress, a fast response, and a very low electric current. Their properties [1, 3, 4] are dependent on certain important variables, such as shear rate, electric field, frequency, fluid composition, temperature, addition of additives, etc.

Over the last two decades, ER fluids have fascinated many scientists, engineers, and inventors because they can be used to control vibration [3, 4] and damping [5, 6] through the application of high electric fields; they can also be used as an interface between mechanical and electronic systems to produce an automatic control process in real time. Certain industrial products have been developed using ER fluids, such as clutches and brakes, vibration insulators, shock absorbers [7], etc. However, the presence of many technical problems such as particle sedimentation, fluid heating [8] and the need for high electric fields, has tended to limit their industrial application [9, 10]. Researchers [11, 12] are trying to overcome all these problems, but they are facing great difficulty owing to the fact that the ER fluid performance depends not only on the mixture of fluids and particles, but also on many other factors, such as shear rate, electric field strength, electric field frequency [13-15], humidity, temperature, particle concentration [16, 17], particle size, particle geometry [18], density ratio between the particles and fluid, surfactant [19], etc.

To study the effect of certain independent variables on the shear stress and viscosity, an experimental design has been developed with a view to enabling a quantitative statistical analysis and to identifying the significant parameters that affect the dependent variable. This method is particularly efficient when interactions between various independent parameters can affect dependent variables [20-22]. Therefore, it is a powerful tool in understanding and predicting the effects of certain factors on the application of rheological behaviors. In this paper, we focus on observing the influence of particle concentrations, particle sizes, surfactants, electric fields and shear rates on ER fluid shear stress, and thus on developing an efficient ER fluid by the experimental design. A series of home-made ER fluids called ETSERF are developed, and consist in a suspension of diatomite powders dispersed in silicon oil with a surfactant TWEEN80 (Polyethylene glycol sorbitan monooleate). This study describes the results of analyses of variance (ANOVA) of the rheological behavior of the ETSERF fluids. A quantitative relationship between the dynamic shear stress and the independent variables is established. This relationship is based on the Bingham model, and provides an explanation for the contributions made by each independent parameter on the viscosity and yield stress of the ETSERF fluids. An empirical model, named the Quasi-Bingham model, is proposed, and is a universal equation obtained through a regression method that may be applied to all kinds of ER fluids with a shear-thinning behavior. The empirical model enables the prediction of the influence of dependent variable parameters on yield stress and viscosity.

3.2 Rheological Behaviour of ETSERF

A cylindrical rotary viscometer (Couette), designed and manufactured according to ISO 3219 [23], is used for shear stress measurement. It combines a speed control system and an amplifier/supply high-voltage system (10 kV) allowing it to establish an automatic measurement of shear stress versus shear rate. Figure 3.1 presents a diagram of the Couette viscometer.

The investigated fluid is filled between the two coaxial cylinders, and the shearing laminar motion of the ER fluid is obtained through the rotation of the inner cylinder, which may have various uniform rotational speeds. The outer cylinder is free to rotate, and will apply a force on a flexible beam instrumented with a strain gauge during the shear motion of the ER fluid, after which the shear stress is computed from the strain gauge reading.

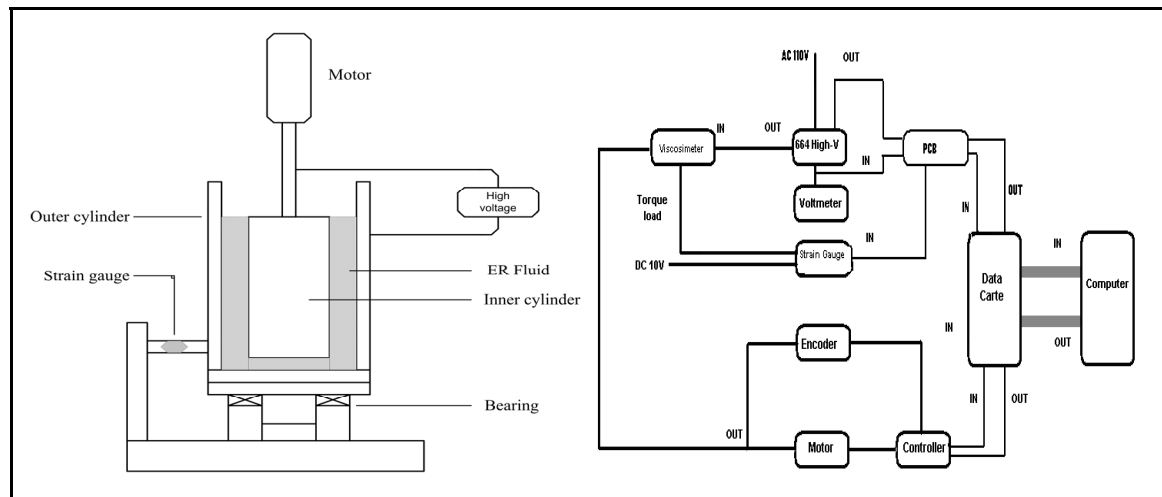


Figure 3.1 Couette viscometer.

3.2.1 Rheological Behaviour of Various ER Fluids

To allow an investigation of the particle effect, seven ER compositions have been analyzed and compared. Five of them were prepared in the laboratory: 28% of TiO_2 particles dispersed in silicon oil [24], 28% of Al_2O_3 particles [25, 26] dispersed in silicon oil, 25% of cacao particles dispersed in olive oil, ETSERF20 and ETSERF40. Among these ER fluids, the ETSERF20 and ETSERF40 are home-made ER fluids composed of diatomite: 20 and 40 in the fluid names indicate the particle sizes in micrometers. The two other fluids tested were commercial products: Rheobay TP AI 3565 from Bayer-Silicone [27] and VersaFlo ER 100 from Lord Corporation [28]. Figures 3.2(a), (b) and (c) show the comparative rheograms for the investigated mixtures under DC electric field strengths of 0 kV/mm, 1 kV/mm and 2 kV/mm, respectively.

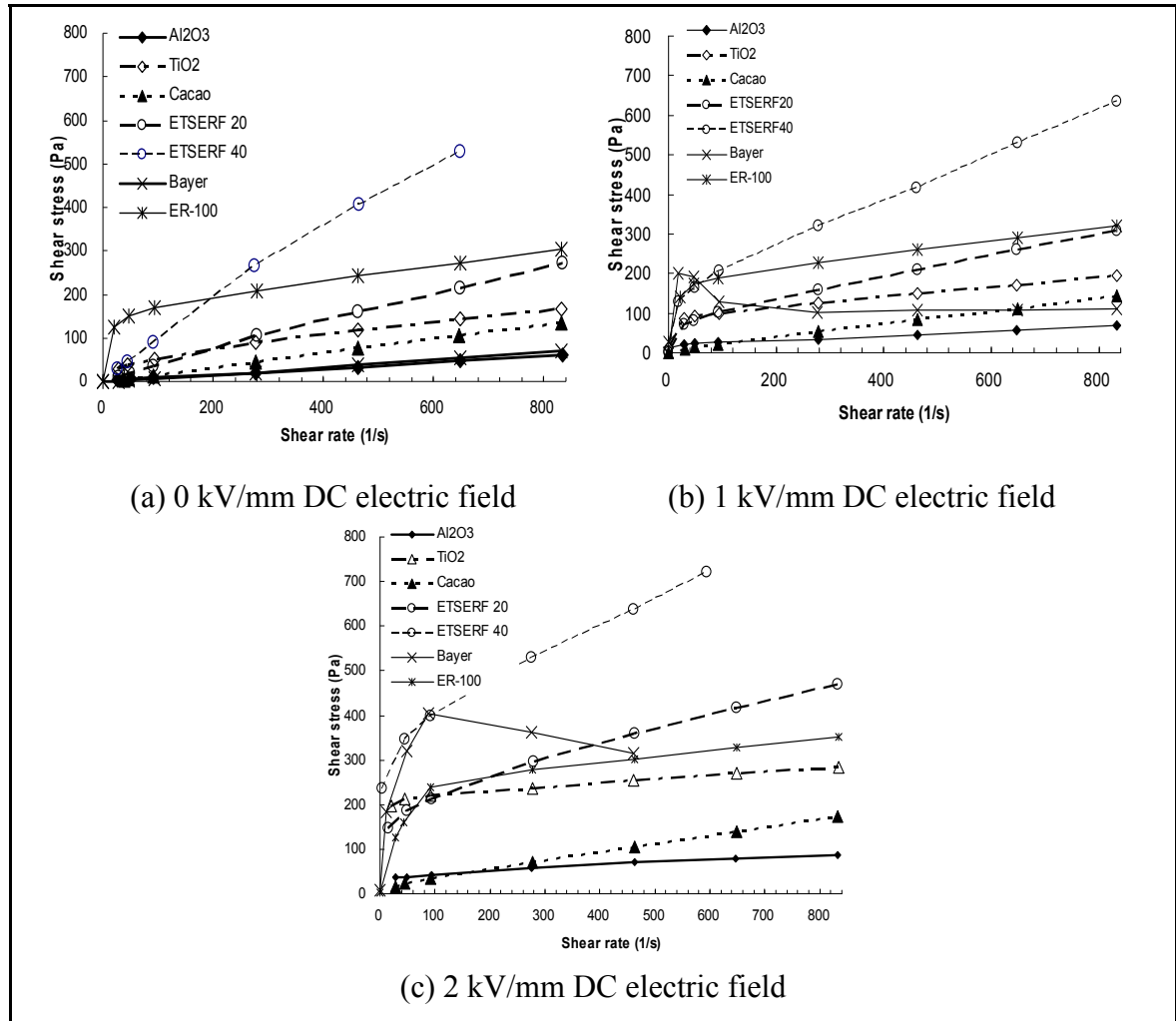


Figure 3.2 Rheograms of ER fluids for various ER fluids.

Figure 3.2 shows that all these mixtures, except VersaFlo ER-100, present a quasi-Newtonian behaviour without the electric field applied. These ER fluids all exhibit non-Newtonian characteristics with different rheological responses under high electric fields. The Al₂O₃ ER fluid with silicon oil and the cacao-ER fluid with olive oil present weak ER effects, while the RheoBay fluid and VersaFlo ER-100 present good ER performances at low shear rates. However, the ETSERF mixtures show great improvement in ER performance for a wide shear rate range, especially at a high shear rate. Based on these results, we concentrated our research efforts in this study on the development of the ETSERF fluids composed of diatomite particles.

3.2.2 Preparation of ETSERF Fluids

3.2.2.1 Diatomite Particles

The ETSERF is a new mixture in which diatomite particles are immersed into silicon oil with a surfactant TWEEN 80 (Polyethylene glycol sorbitan monooleate). The diatomite powder was selected because of its honeycomb structure, and due to the fact that it has certain useful characteristics, such as a high absorptive capacity, a large surface area, a high chemical stability, and a low bulky density. The density of the diatomite powder is 2.1 g/cm^3 [29]. Figure 3.3 presents the microstructure of diatomite.

The diatomite particles selected were divided into two categories, according to their mean sizes. One batch, called *crunched*, was crunched, while the other, called *uncrunched*, was kept as received; the particle sizes were inspected using an optical microscope, and the uncrunched batch, called ETSERF40, had an average diameter of $40 \text{ }\mu\text{m}$, while the crunched batch, called ETSERF20, had an average diameter of $20 \text{ }\mu\text{m}$. The particle geometry of the ETSERF20 changes because some honeycomb structures break down as the particle size is reduced. The particle size distributions are illustrated in Figure 3.4.

The dielectric fluid is silicone oil S159 from Fisher Scientific, which has a viscosity of $1 \text{ mPa}\cdot\text{s}$ (at 25°C), a density of 0.96 g/cm^3 , a relative dielectric constant of 2.76, and an electric conductivity of $1.47 \times 10^{-15} \text{ S/m}$. The moist diatomite powder was initially chosen with a mass concentration of water of 0.3%. The dielectric characteristics can be modified by varying the humidity of the diatomite powder in order to obtain a good ER suspension. A comparison of the ER effects of moist and dry particles under different electric fields is illustrated in Figure 3.5. These rheological curves show the obvious effect of the humidity of the particles when an electric field is applied. This study focuses on the ETSERF with moist diatomite particles because it clearly ensures better ER efficiency.

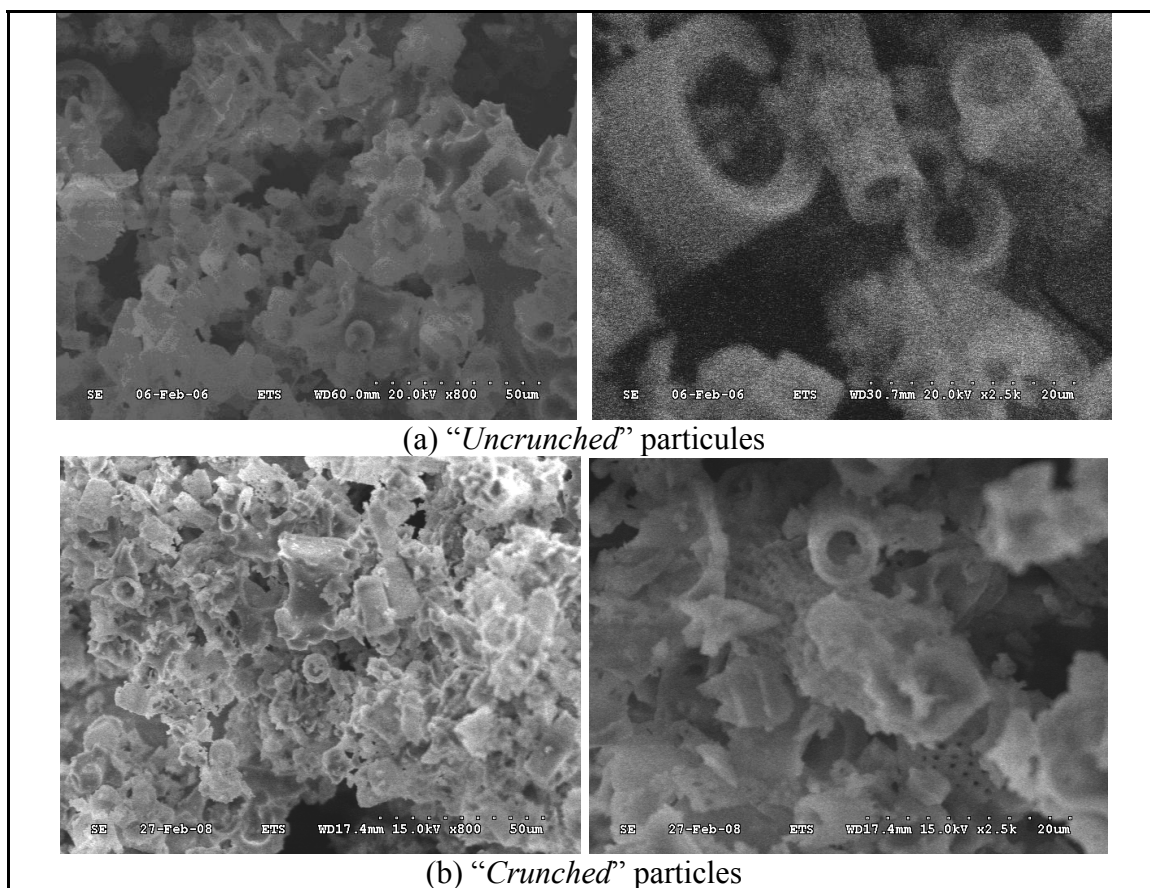


Figure 3.3 Microstructure of diatomite particles under electric microscope.

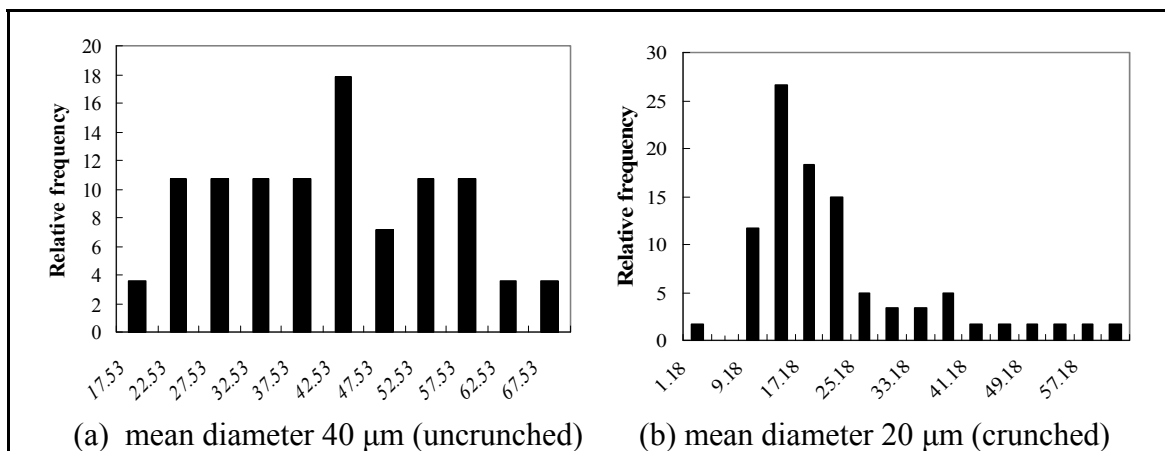


Figure 3.4 Particle size distributions.

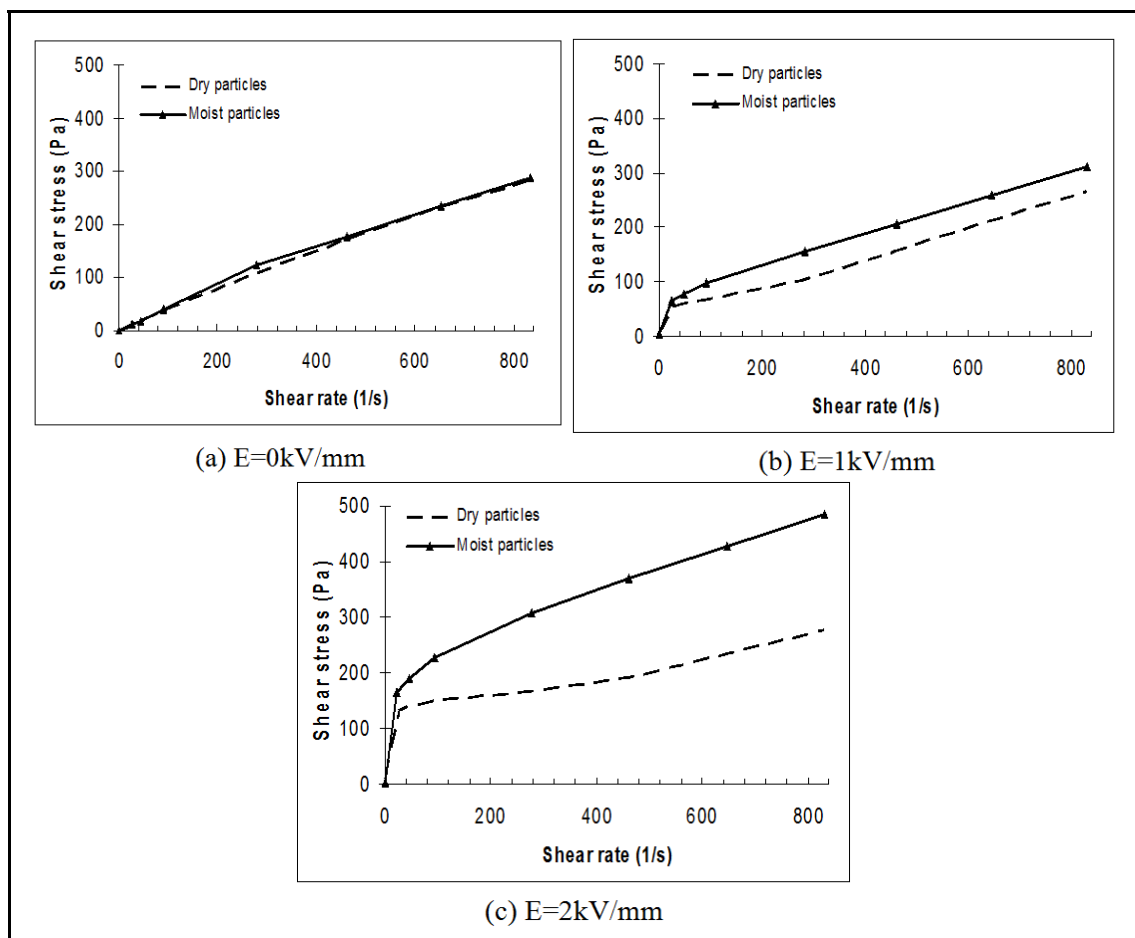


Figure 3.5 Comparison of ER effects with dry and moist diatomite powders.

3.2.2.2 Optical observation of chain formation

The chain formation of ETSEF fluids under an electric field was visualized using an optical microscope. The experimental set-up is presented in Figure 3.6. The ER fluid was filled in the space between two electrodes, and electric fields of 0 kV/mm, 1 kV/mm and 2 kV/mm were applied, respectively.

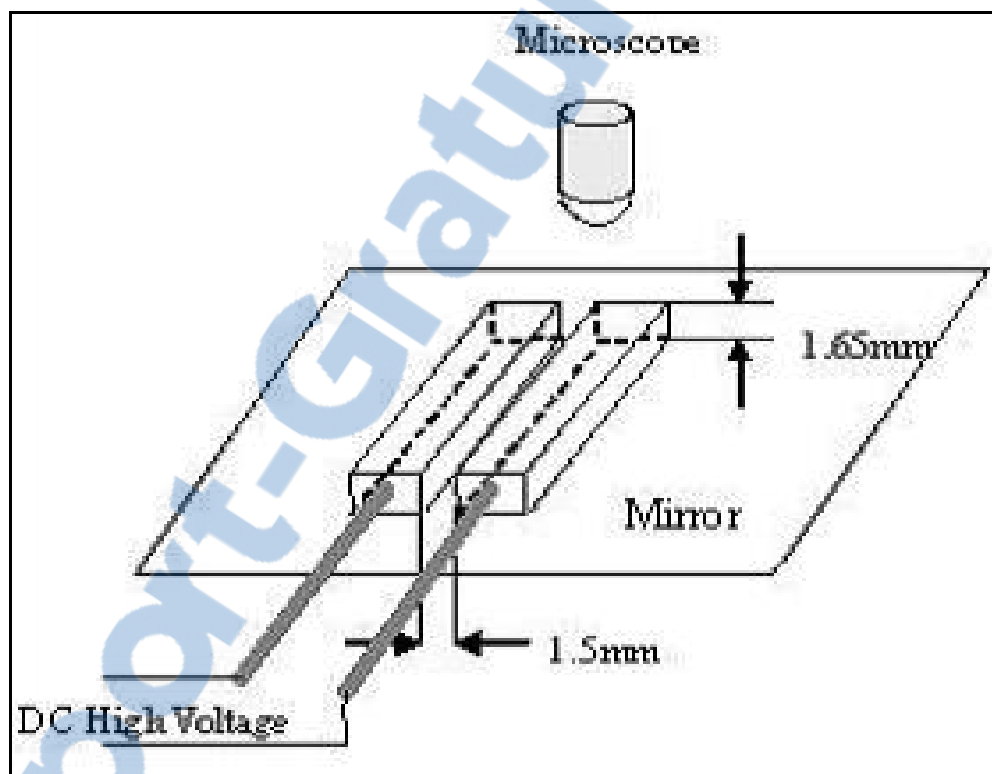


Figure 3.6 Observation of ER fluids using optical microscope.

In Figure 3.7, when the electric field is applied, many chain formations can be observed, resulting from the interaction between the polarized particles induced by the electric field. Under an electric field, an agglomerative phenomenon appears at the surface of the positive electrode. It can be also seen in Figure 3.7 that the chain formation strongly depends on the electric field strength.

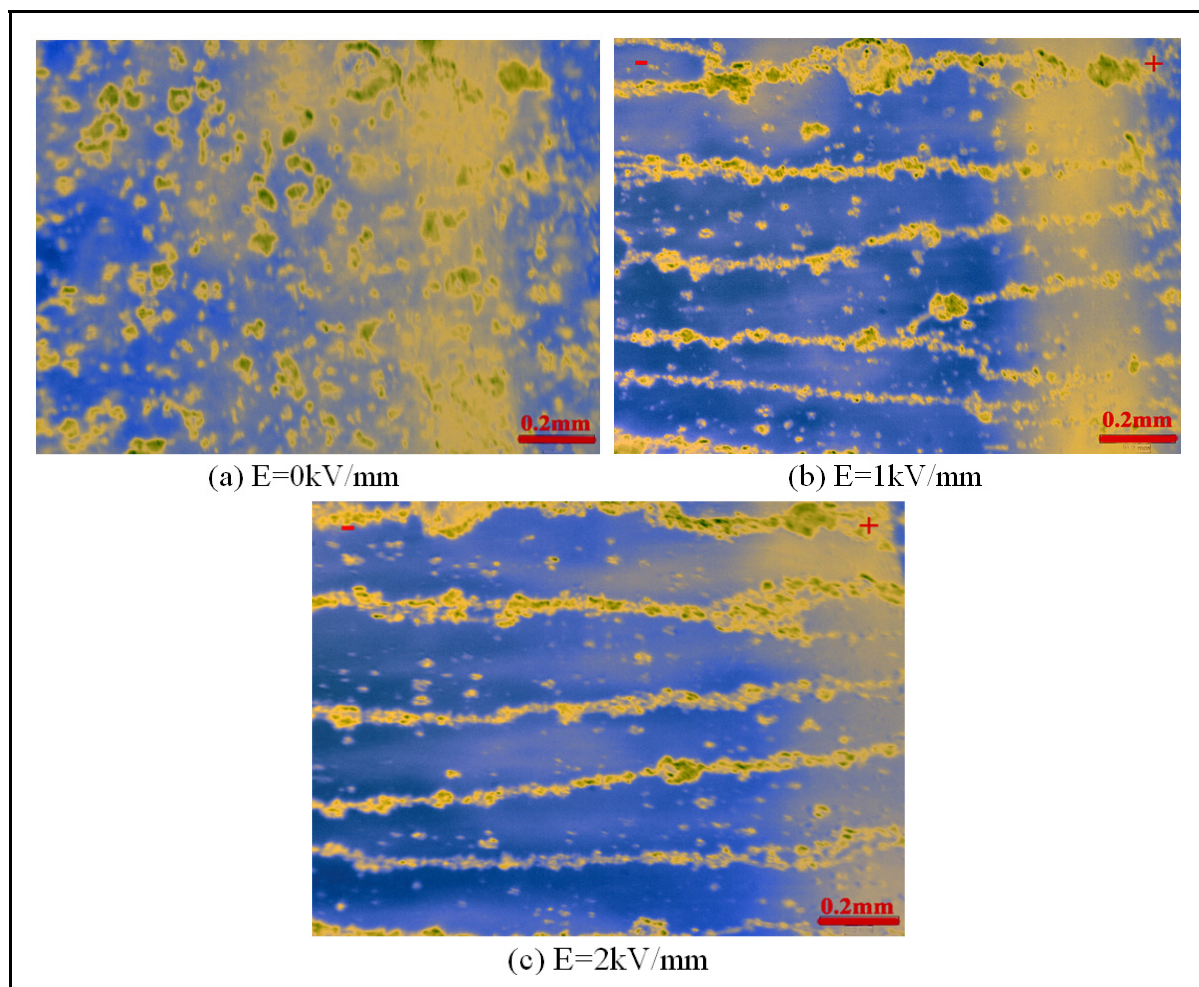


Figure 3.7 ETSERF chains under various electric fields.

3.2.3 Measurement of dielectric and dynamic properties of ETSERF

The ER characteristics are not only related to the electric field, the shear rate, the particle concentration, the particle size, but rather are linked to other factors, such as dielectric properties, electric field frequency, time response, etc.

3.2.3.1 Electrorheological response under AC electric field in ER fluid

ER fluids produce different effects under different frequencies of alternative electric field [13-15, 25]. In the present work, the electrorheological responses of the ER fluids excited by alternative electric fields were studied. The measurements were conducted under 0-300 Hz for both the ETSERF20 and ETSERF40. Figures 3.8(a) and (b) show the frequency dependence of the ETSERF on the shear stress at various shear rates.

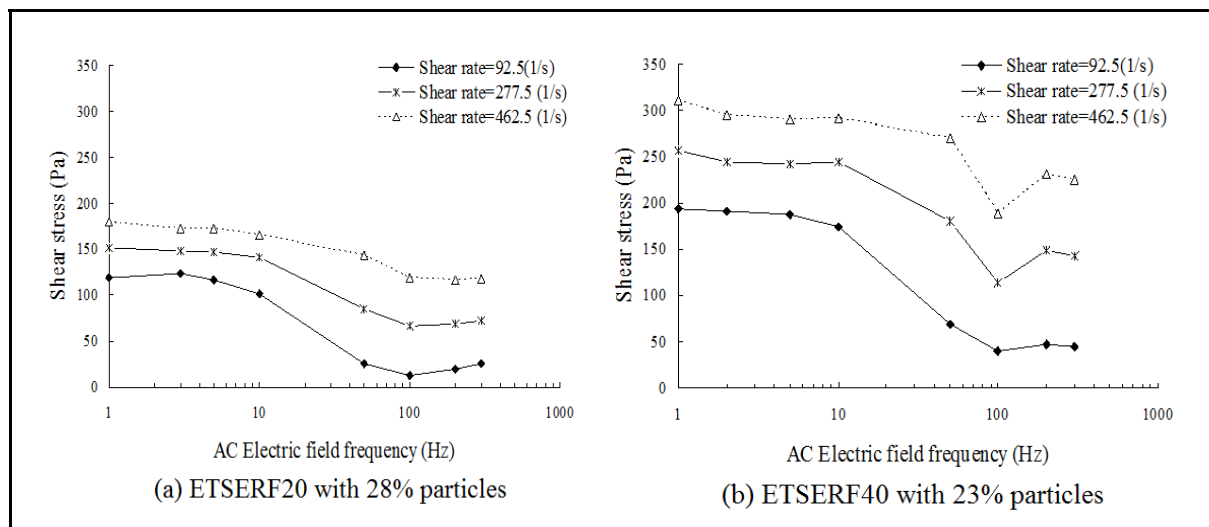


Figure 3.8 Frequency dependence of shear stresses at different shear rates under 2 kV/mm electric field strength.

Figure 8(a) describes the behavior of the ETSERF20 with a high particle mass concentration (28%), while Figure 8(b) presents those of the ETSEFR40, with a low particle mass concentration (23%). In Figure 3.8, the maximum shear stress values occur at low

frequencies (0-10Hz). It can be observed that the shear stresses decrease as the electric field frequency increases beyond 10 Hz, and reach a minimum point at close to 100 Hz. Note that a similar phenomenon was observed by Jones et al [30], and that it may be explained by the fact that the rotation of particles could reduce dynamic ER effects. When the electric field is applied, the particle chain structure is created as a result of polarization, the particles orientate in the direction of the electric field, but this quiescent structure restricts hydrodynamic flow. When the structure experiences larger boundary movements or high shear rates, the particles undergo a rotational motion with structural rearrangement, thus causing the dynamic ER effect to decrease in most cases. This result suggests that an automatic control for adapting the shear stress could be established by varying the electric field frequency between 10 and 100 Hz.

3.2.3.2 Transient response of ER fluids

The transient response of ER fluids is another important factor used to describe their ER behaviour. The transient responses of the ETSERF20 fluids were observed under both a square-wave and a step-wave electric field excitation. Measurements were carried out under various electric field strengths.

Figures 3.9(a) and (b) describe the transient responses of the ETSERF20 with a 28% particle concentration under conditions of a square-wave electric field and a step-wave excitation at a low shear rate of 185 (1/s). In Figure 3.9, two electric field strengths of 1 kV/mm and 2 kV/mm are applied. The results from the square-wave test (Figure 3.9(a)) show that the ETSERF20 responds to an electric stimulation 1.2 seconds after the transient response is damped, and then retrieves its initial value in 0.2 seconds. The results from the step-wave test (Figure 3.9(b)) show that the higher the electric field, the faster a stable response is obtained.

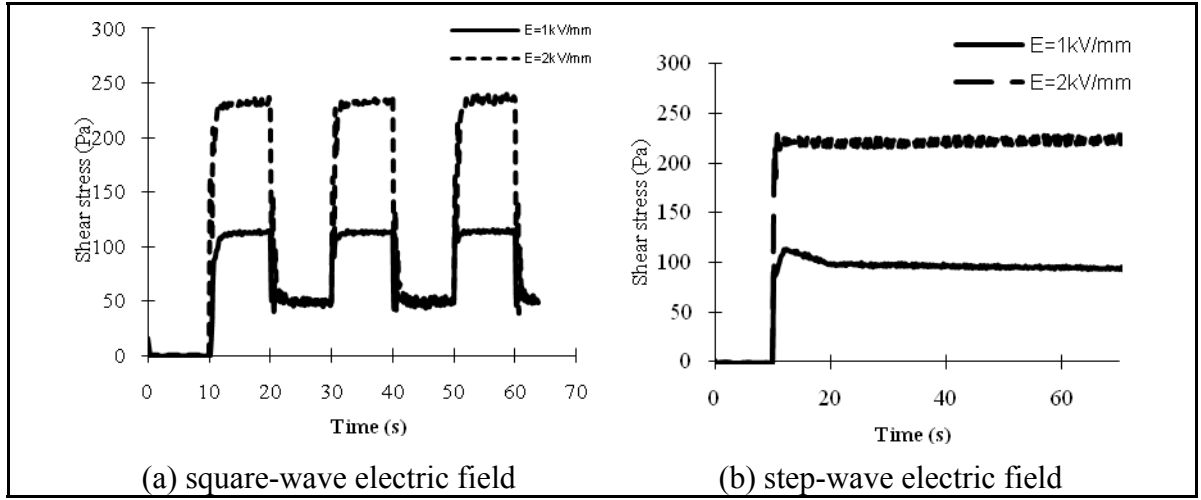


Figure 3.9 Transient responses of ETSEF20 with 28 Wt% at shear rate of 185 (1/s).

3.2.3.3 Dielectric proprieties of ETSEF fluids

The complex dielectric constant ϵ^* is usually written as [31]:

$$\epsilon^* = \epsilon' - i\epsilon'' = \epsilon'(1 - i \tan \delta) \quad (3.1)$$

where ϵ' is dielectric constant, ϵ'' is dielectric loss, and $\tan \delta$ is the loss tangent (or loss factor).

The relaxation frequency is defined by a local peak of dielectric loss. Block et al [32] indicated that the relaxation frequency of ER fluids is proportional to their rate of polarization, and that a good ER fluid must exhibit a relaxation frequency in the range of 10^2 - 10^5 Hz [33]. The dielectric property of the ER suspension was measured using a Novocontrol broadband dielectric spectrometer with a frequency range of 10^{-1} to 10^5 Hz. The fluid was filled in a coaxial cylinder sample container, the electric champ is applied to the inner and outer cylinder, and the dielectric constant ϵ' and dielectric loss ϵ'' of the ETSEF fluid were measured at 23°C according to standard test methods [34]. The dielectric constant ϵ' and dielectric loss ϵ'' of the ETSEF were measured with and without a surfactant, respectively,

using combinations of two mass concentrations (23 and 28%) and two particle sizes : 20 and 40 μm (Figure 3.10 (a) and (b)).

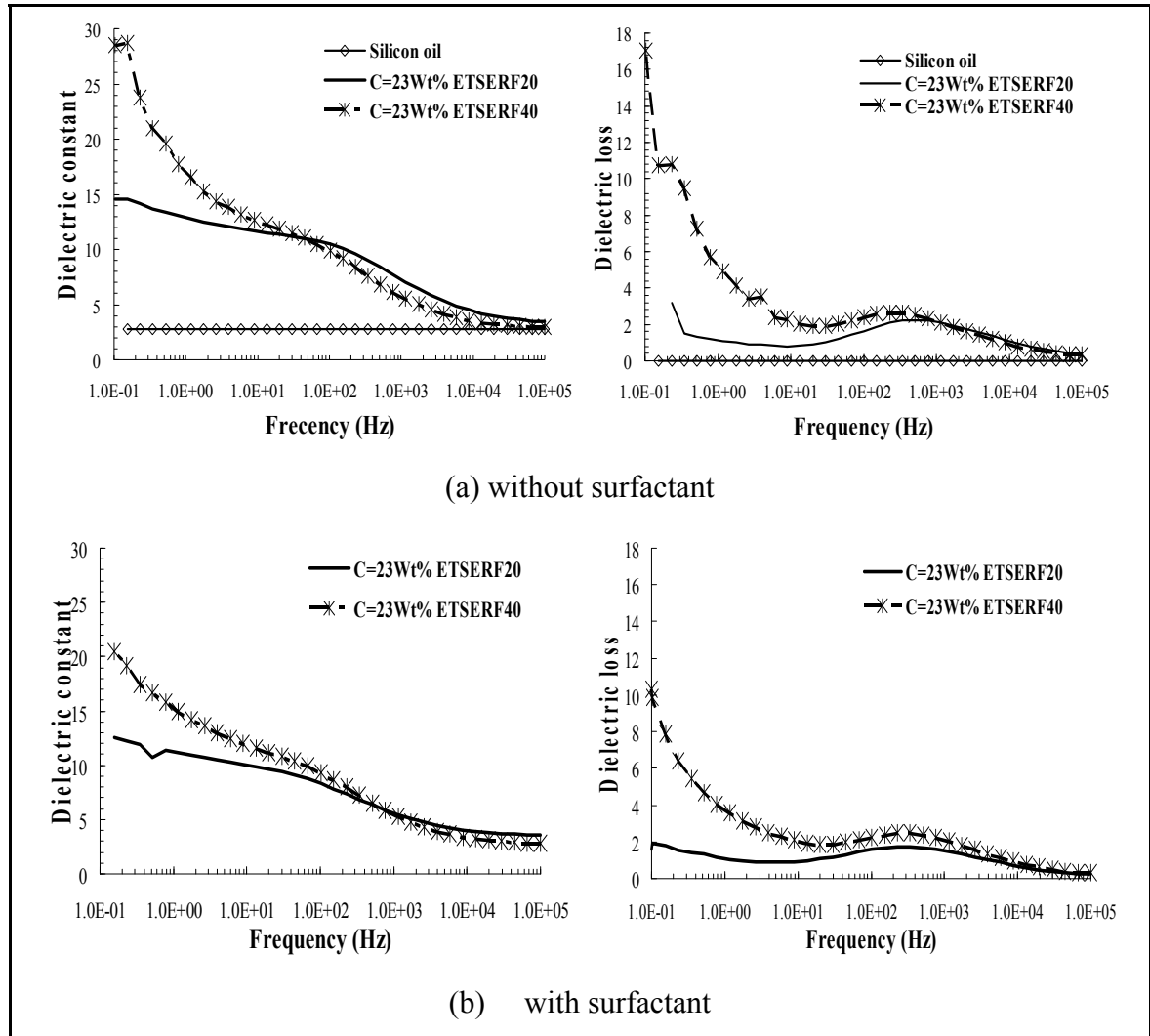


Figure 3.10 Dielectric constant (ϵ') and dielectric loss (ϵ'') for ETSERF fluids with different particle sizes.

The effect of the particle sizes on dielectric behaviour can clearly be observed in Figure 3.10(a). The dielectric constant of the ER fluids increases as the particle sizes increases, especially at low frequencies. The results also show that the relaxation frequency peak is

around 500 Hz for the ETSERF20, and at about 300Hz for the ETSERF40. When a surfactant is added, the two peaks decrease to around 300 Hz and 200Hz, respectively.

An ER fluid with large particles exhibits a higher ϵ'' than one with small size particles. This implies that ER fluids using large particles will dissipate more power when polarized, because dielectric loss represents the dissipation energy, and the greater the dielectric loss, then the higher the energy dissipated by the material. The dielectric parameters decrease somewhat with the addition of a surfactant, but it is recommended for use in slowing down sedimentation as it can stabilize the ER fluid.

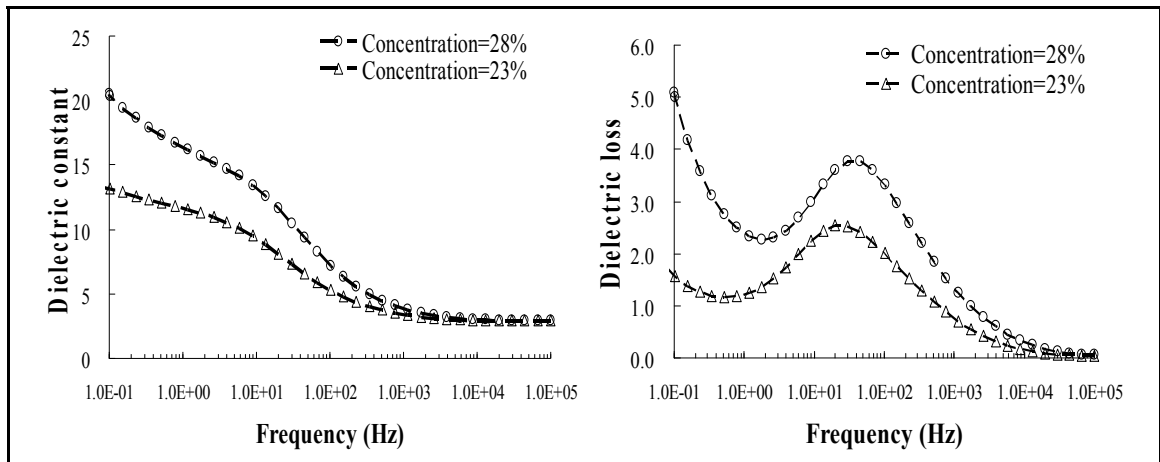


Figure 3.11 Dielectric constant (ϵ') and dielectric loss (ϵ'') for ETSERF fluids with different particle concentrations.

Figure 3.11 shows the results of the dielectric properties under different mass concentrations for the ER fluids with dry particles. It can be seen that the dielectric constant depends on the particle concentration, and significantly increases with an increase in particle concentration at low frequencies. The relaxation frequency, observed from the peak in Figure 3.11(b), also changes with the particle concentrations. That is especially the case for a 28% particle concentration, where the conductivity increases more rapidly at low frequencies than with a 23% concentration. Thus, due to the ER fluid interfacial polarization under an electric field, a

large particle concentration (in this considered range) may be recommended in designing the ETSERF.

3.2.3.4 Relation between the ageing of ETSERF and dielectric loss

The ER and dielectric properties of an ETSERF40 suspension, with a concentration of 23% of dry particles, were observed for more than 72 hours in order to study the effect of fluid ageing. Figure 3.12 shows the rheograms of the ETSERF at various electric fields. It can be seen in Figure 3.12 that the ageing duration has no significant effect on shear stress when no electric field is applied. However, this effect becomes significant after ageing when the electric field is applied, especially with a relatively high electric field (2 kV/mm). For example, the shear stress decreases from 394Pa to 193Pa at a 462 (1/s) shear rate under a 2 kV/mm electric field strength during ageing. If we define this phenomenon as the ageing of ER fluids, then the ER properties and the dielectric properties (mainly the dielectric loss) are strongly dependent on the duration of ageing. This ageing phenomenon may be due to the fact that the particles agglomerate into bigger particles.

It can be seen in Figure 3.13 that there are significant variations in the dielectric constant, particularly in the relaxation frequency range. The relaxation frequency decreases from 30 Hz to 0.2 Hz for ageing taking place over 72 hours. In theory, the smaller the relaxation frequency, the slower the response for establishing a polarization, thus indicating that the ER system needs a longer time to form particle chains. In shear mode, there will not be enough time to form particle chains at a relative high shear rate, and therefore, the ER efficiency will be reduced.

All these results suggest that better ER performances will be obtained at low frequencies, and consequently, the experimental design should be conducted under a DC electric field.

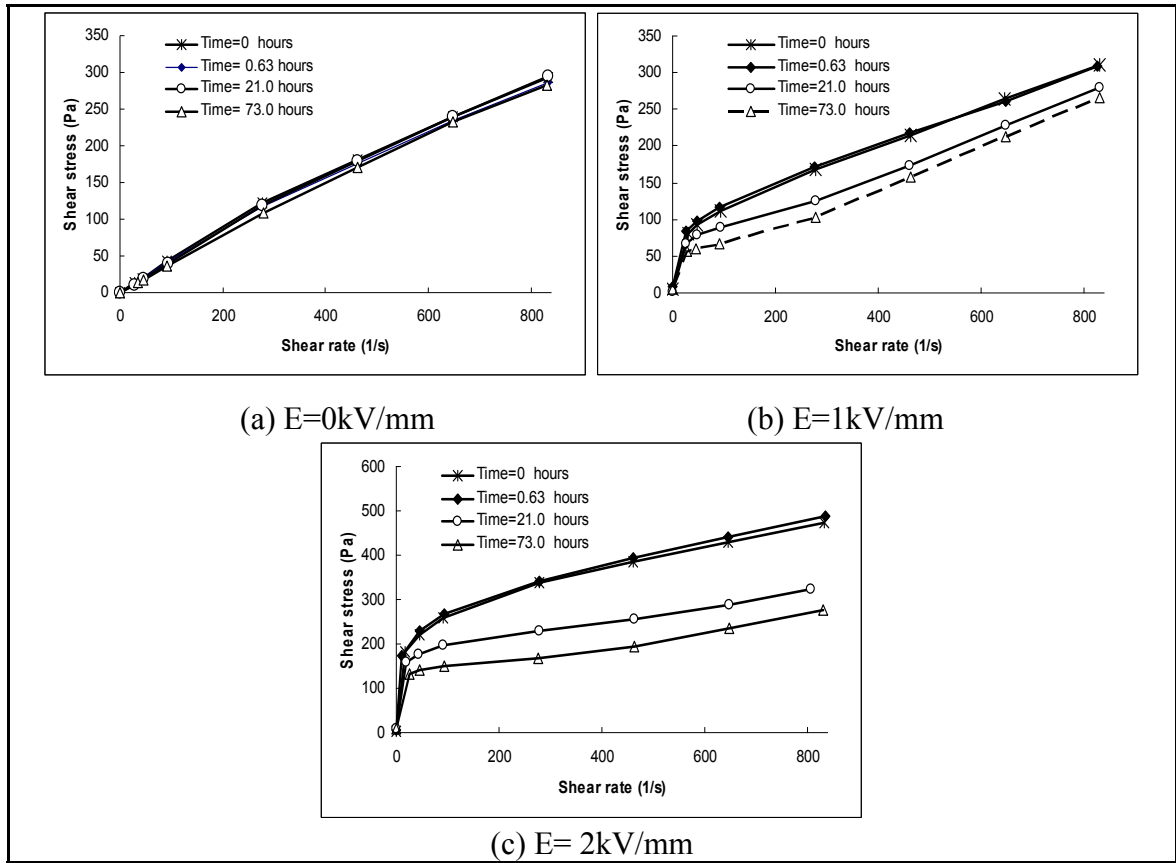


Figure 3.12 Observation of the ageing of ETSERF40.

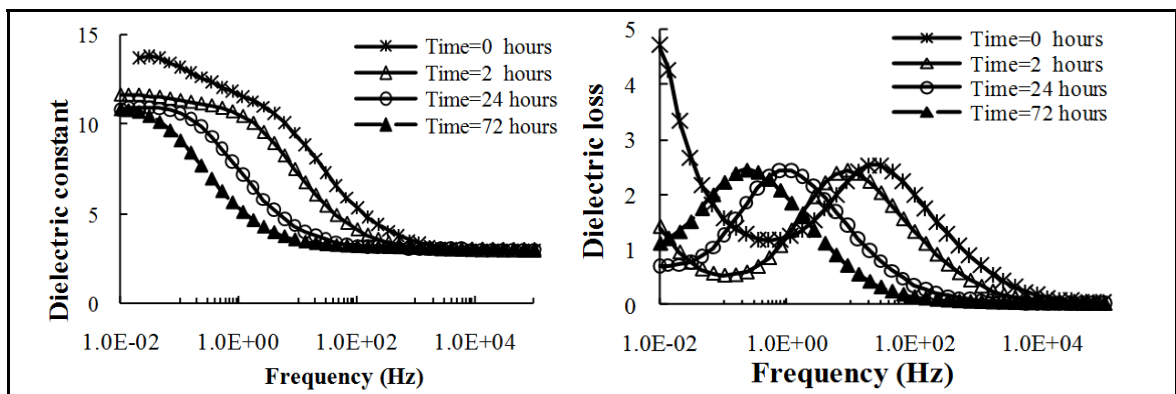


Figure 3.13 Dependence of dielectric properties on time for ETSERF with a 23% concentration and dry particles.

3.3 Experimental Design and Procedure

3.3.1 Design of Experiment

The experimental design method is a powerful tool for analyzing interactions between parameters that cannot be detected by studying one parameter at a time. The ER fluid behaviour depends mainly on the particle concentration in the liquid [16, 17], the electric field [13-15, 24], the shear rate, the surfactant [19, 25, 26], particle sizes, and the particle geometry [18]. A ‘Complete Multilevel Factorial’ design was selected in order to allow all interactions between the independent variables to be investigated effectively. We chose different levels for each independent variable: two-level for the particle size and surfactant, three-level for the particle concentration and the electric field, and four-level for the shear rate. The particle mass concentration was limited to around 28% in order to avoid a saturation of the mixture. The levels of the independent variables are shown in Table 1 and the shear stress (Pa) was selected as a dependent variable. The tests were repeated twice in order to increase result confidence, and a total of 288 tests were conducted in order to obtain all possible combinations of the variables.

Table 3.1 Levels of independent variables

Variable	Unit	Level 1	Level 2	Level 3	Level 4
Particle mass concentration	%	18	23	28	
Mean size of particles	μm	20	40		
Surfactant	ppm	0	90		
Electric field	kV/mm	0	1	2	
Shear rate	1/s	93	278	463	648
Repeat		1	2		

3.3.2 Statistical Results Analysis

An analysis of variance (ANOVA) was used to analyze the collected data. A 1% confidence level was selected to test the significance of the main effects and the three level interaction

effects. The computed ANOVA output and the calculated F ratios are shown in Table 3.2 for each significant effect.

All F ratios were calculated based on the residual mean square error. The ANOVA table decomposes the variability of the shear stress into the contributions of various factors. Type III sums of squares were chosen, and the contribution of each factor was measured following the removal of the effects of all other factors. A P-value is used to test the statistical significance of each of these factors. When a P-value is less than 0.01, the factor has a statistical significant effect on shear stress at the 99.0% confidence level.

The results in Table 3.2 are classified by the order of the Fisher significance. The main effect analysis shows that the significant parameters, classified from the most to the least important, are particle concentration, electric field, particle size, shear rate, and surfactant. The ANOVA analysis reveals that apart from for the shear rate-concentration-surfactant and shear rate-surfactant-size, all three-level interactions are significant. To analyze the three-level interactions, one parameter was kept constant, and the effects of the two others were plotted. The analyses are classified by order of significance, in accordance with the Fischer indices. All significant three-level interactions are illustrated in Figures 3.14 to 3.21, along with their respective confidence intervals.

Table 3.2 Analysis of variance for shear stress

Source	Sum of Squares	DOF	Mean Squares	F-Ratio	P-Value
Main Effects					
C: Concentration	1936490	2	968243	3151	0.0000
B: Electric field	1456430	2	728216	2370	0.0000
E: Size	643324	1	643324	2094	0.0000
A: Shear rate	891983	3	297328	969	0.0000
D: Surfactant	4826	1	4826	16	0.0001
Three-Level Interactions					
CDE	12669	2	6334	21	0.0000
ACE	34721	6	5787	19	0.0000
BDE	11046	2	5523	18	0.0000
BCE	10833	4	2708	9	0.0000
ABE	15567	6	2594	8	0.0000
BCD	7756	4	1939	6	0.0001
ABD	8232	6	1372	5	0.0003
ABC	12163	12	1014	3	0.0002
ADE	3206	3	1069	4	0.0170
ACD	1825	6	304	1	0.4333
Residual	60223	196	307		0.0000
Total	5781340	287			

3.3.2.1 Shear stress induced by particle sizes and surfactant under different concentrations (CDE)

Figure 3.14 describes the effects of particle concentrations and particle sizes on shear stress with and without a surfactant. It can be seen that increasing the particle concentration (to a maximum level which is lower than the saturation level) and particle size have a beneficial effect on the shear stress. The surfactant has no significant effect, and has a negative effect on ER performance when the fluid mixes with a high concentration of uncrunched particles (see Figure 3.14 (b)).

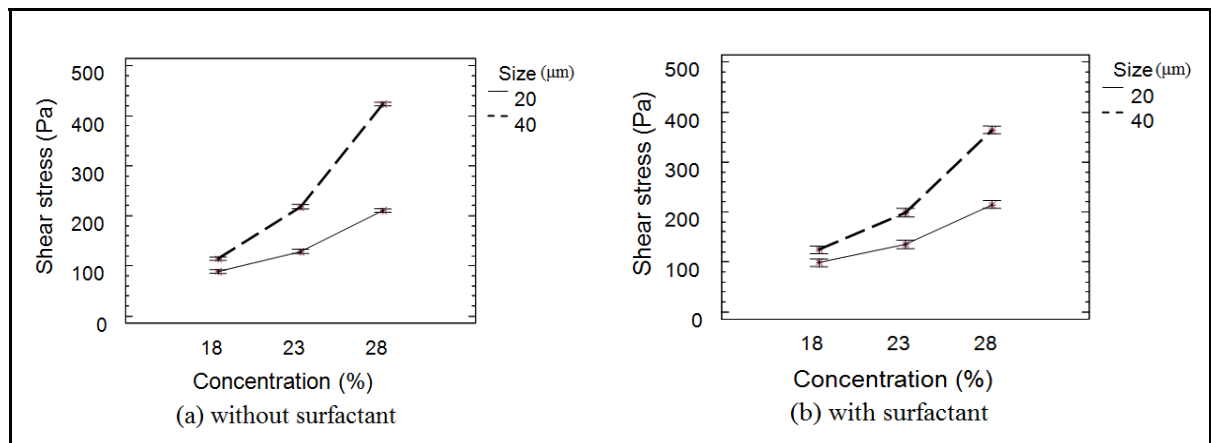


Figure 3.14 Effect of particle concentration and size on shear stress.

3.3.2.2 Shear stress effect induced by shear rate, particle concentration and size (ACE)

Figure 3.15 shows the effects of the interaction of the shear rate and particle mass concentration on the shear stress, using two particle sizes: (a) a large (uncrunched) size (40 μm), and (b) a small (crunched) size (20 μm). The shear stress increases with increases in the particle size, particle concentration, and shear rate. This effect is more pronounced when a high concentration (28%) is combined with large particles (40 μm).

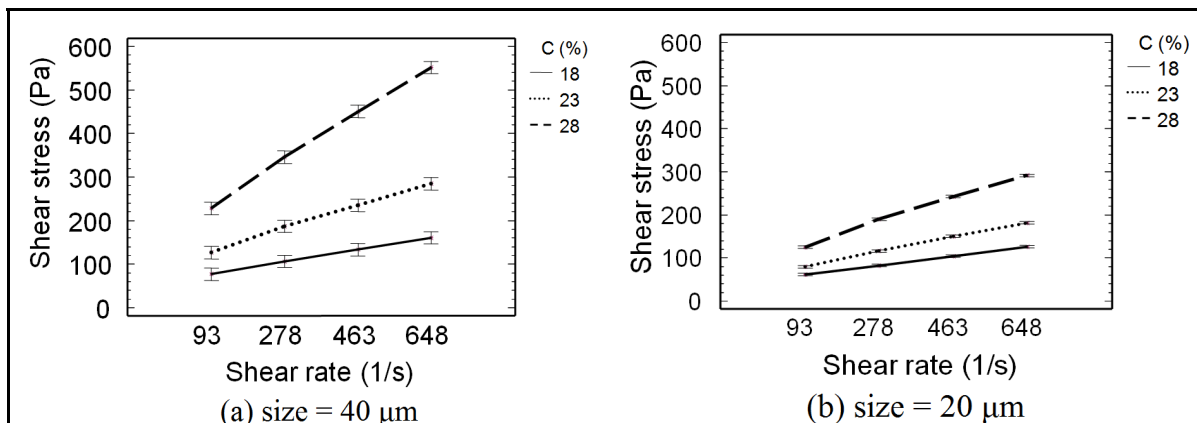


Figure 3.15 Effect of shear rate and particle concentration on shear stress.

3.3.2.3 Shear stress induced by electric field strength, the surfactant and particle size (BDE)

Figure 3.16 shows that increase in the electric field and particle sizes lead to a high shear stress. As expected, the increase in the shear stress is along with the electric field following a 2-order polynomial function. The surfactant induces a small negative effect (40 Pa) for uncrunched particles when an electric field is applied.

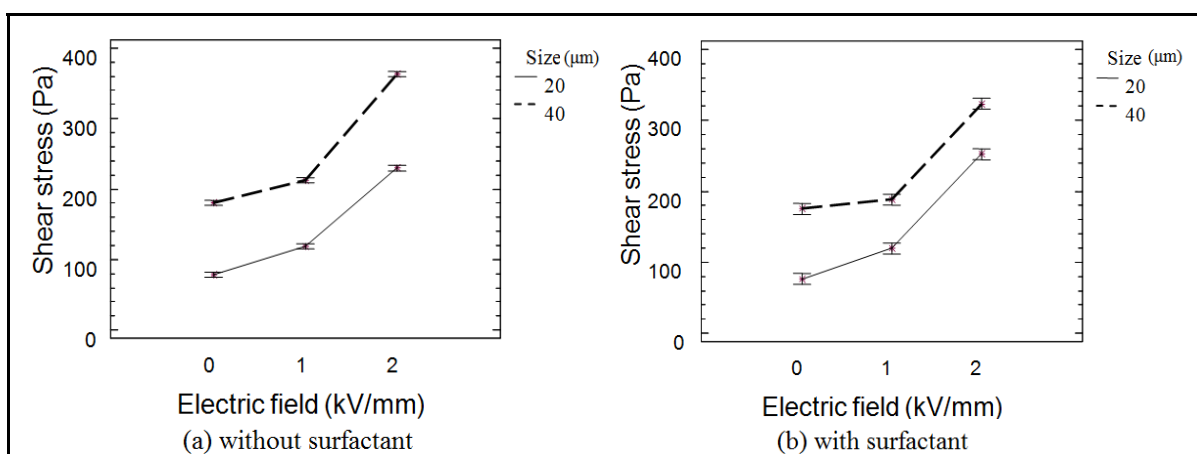


Figure 3.16 Effect of electric field strength and particle size on shear stress.

3.3.2.4 Shear stress effect induced by the size and electric field strength under different concentrations (BCE)

Figure 3.17 shows the effects of the interactions of the electric field and particle mass concentrations on the shear stress for (a) uncrunched particle sizes, and (b) crunched particle sizes. It can be seen that the shear stress increases with increases in the particle concentration, particle size, and electric field strength. However, the stress variation does not have a significant effect when the fluid is composed of uncrunched particles and a high concentration under a low electric field strength (1 kV/mm) (Figure 17 (a)).

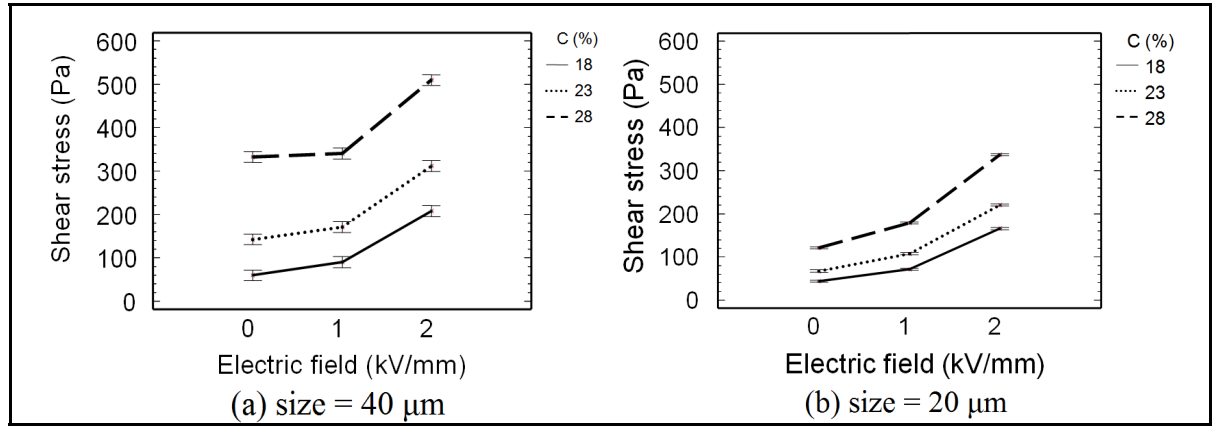


Figure 3.17 Effect of electric field strength, particle mass concentration and size on shear stress.

3.3.2.5 Shear stress effect induced by the electric field strength and the shear rate under different sizes (ABE)

The experiment curves in Figure 3.18 (a) and (b) show that the shear stress increases along with increases in the shear rate, electric field, and particle size. However, when uncrunched particles are used and a weak electric field (1kV/mm) is applied, decent ER performance is only obtained at low shear rates. The electric field must exceed 1 kV/mm for a significant effect (Figure (3.18 (b))) to be observed at a high shear rate.

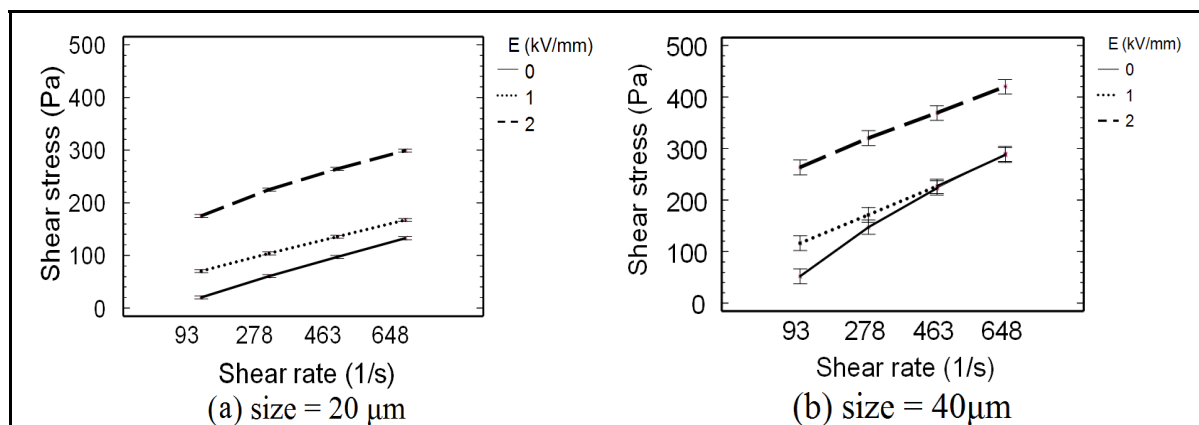


Figure 3.18 Effect of shear rate and electric field strength on shear stress under different particle sizes.

3.3.2.6 Shear stress induced by electric field strength and the surfactant under different concentrations (BCD)

Figure 3.19 illustrates the effects of the electric field and particle concentration on the shear stress with and without a surfactant.

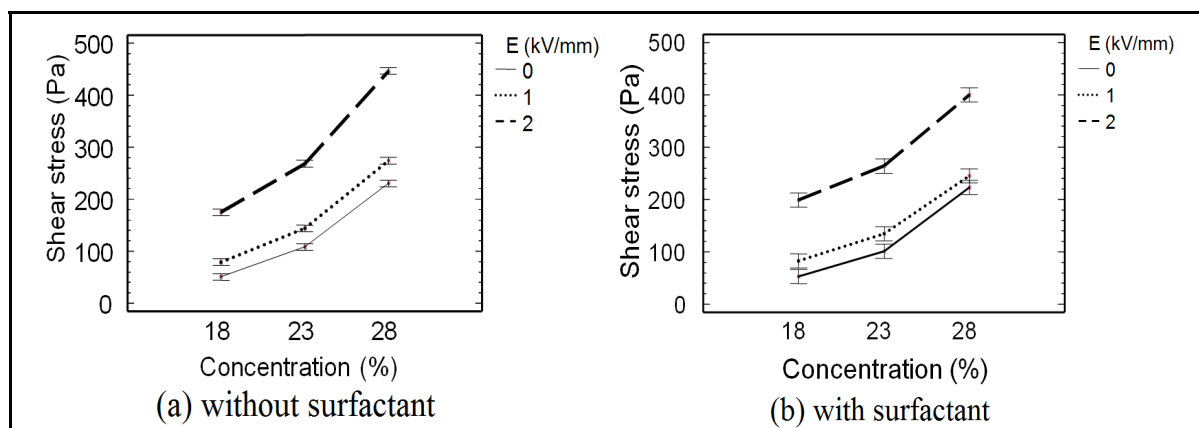


Figure 3.19 Effect of electric field strength, mass concentration and surfactant on shear stress.

Generally, the mixtures with a surfactant exhibit a small decrease in shear stress (50 Pa), except when the fluid works under a condition involving a low particle concentration and a

high electric field. In this study, however, the use of a surfactant may be recommended in order to slow down the sedimentation of particles in the ER fluid.

3.3.2.7 Shear stress effect induced by the electric field strength, the shear rate and surfactant (ABD)

Figures 3.20 show the effects of the electric field and shear rate on the shear stress (a) without a surfactant and (b) with a surfactant. It can be seen that the shear stress increases with increases in the electric field and shear rate. Adding a surfactant produces a small negative effect, especially when a large electric field (greater than 1 kV/mm) is applied at a high shear rate. However, it may also be noticed that the effect of a surfactant is beneficial at low shear rates when a high electric field is applied.

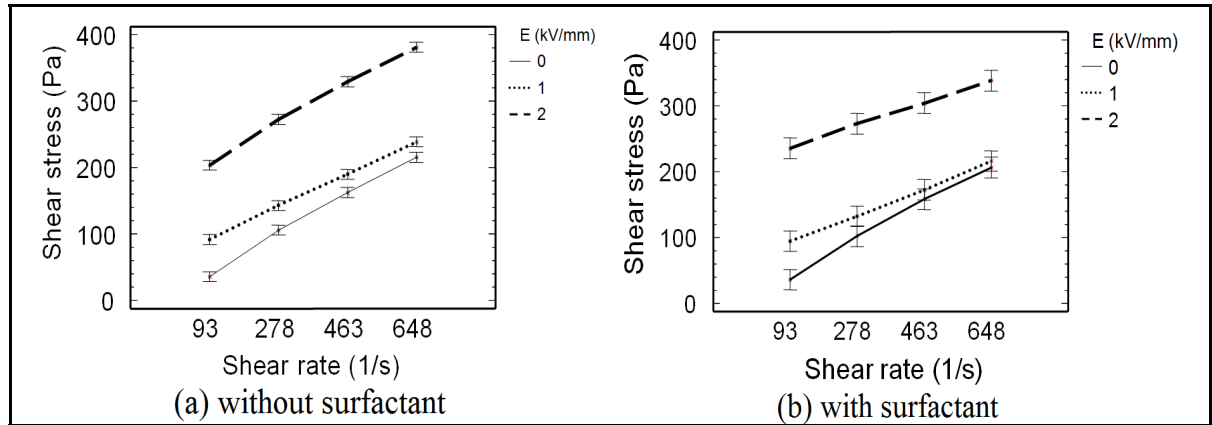


Figure 3.20 Effect of shear rate and electric field strength on shear stress.

3.3.2.8 Shear stress effect induced by the electric field and shear rate under different concentrations (ABC)

The curves in Figures 3.21 (a), (b) and (c) show the influence of interactions between the electric field and shear rate on the shear stress under different mass concentrations (18%, 23% and 28%, respectively). It can be seen that the shear stress increases for all fluids with increases in the shear rate and particle concentration, especially when a high electric field is

applied. However, the ER effect is only efficient at low shear rates when a weak electric field (1 kV/mm) is applied to a 28% particle concentration (see Figure 3.21 (c)). The electric field strength must exceed 1 kV/mm when the fluid is working at a high shear rate.

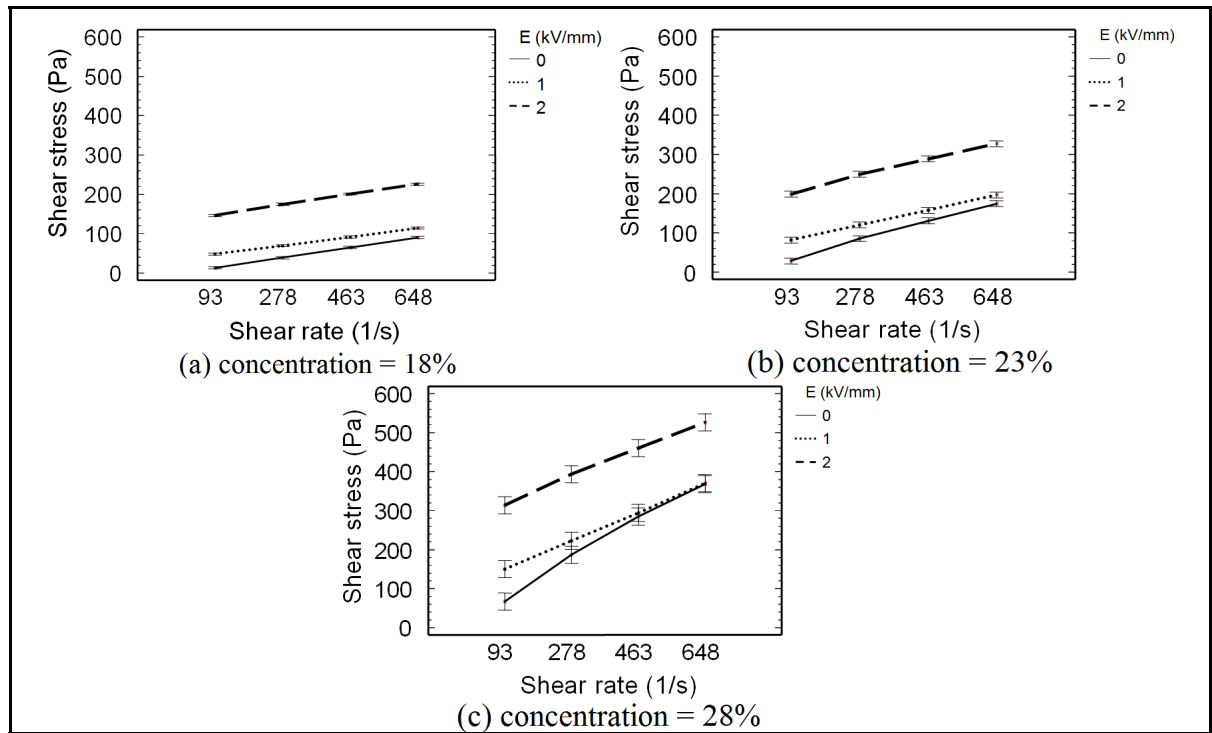


Figure 3.21 Effect of electric field, shear rate and mass concentrations on shear stress.

3.4 Empirical Model for Shear Stress

3.4.1 Quantitative relationship between the dynamic shear stress and the independent variables

The Bingham model is a simple model that has been used for many experimental ER investigations. The viscosity and the yield stress can be modeled as:

$$\tau(E) = \tau_{yB}(E) + \eta\dot{\gamma} \quad (3.2)$$

where, τ is the shear stress (Pa), τ_{yB} is the yield stress, η is the dynamic viscosity(Pa.s), $\dot{\gamma}$ is the shear rate (1/s), and E is the electric field strength (kV/mm).

Unfortunately, this relation does not take into account mixture parameters, such as particle concentration, particle size, and concentration of surfactant, etc. However, the ANOVA analysis allows us to develop an empirical model to satisfy these requirements. Based on the Bingham model and the results obtained from the ANOVA analysis, an empirical relationship can be developed to predict the shear stress as a function of the shear rate, electric field, particle size, and particle concentration, by applying a multiple linear regression method.

The equation of the fitted model is:

$$\tau = (42.86E^2 + 0.895\phi^2E + 0.22\phi dE - 37.83\phi E + 369.67E) + 0.001(1.5\phi d - 0.12\phi^2 - 22d - 0.049\xi d + 1.1\xi)\dot{\gamma} \quad (3.3)$$

where, τ is the shear stress (Pa), E is the electrical field strength (kV/mm), $\dot{\gamma}$ is the shear rate (1/s), ϕ is the mass concentration of particles (%), d is the particle size (μm), and ξ is the surfactant volume concentration (ppm).

This empirical model shows that the shear stress depends not only on the shear rate and the electric field, but also on the particle concentration, particle size, and surfactant. The R^2 statistic indicates that the model accounts for 97.85% of the variability in the shear stress. The adjusted R^2 statistic, which is more suitable for comparing models with different numbers of independent variables, is 97.78%. In determining whether the model can be simplified, we note that the highest P-value of the independent variables is 0.0176. Since the P-value is less than 0.02, the highest order term is statistically significant at the 98% confidence level. Therefore, no variables can be removed from the model. Figure 3.22 shows the predicted values based on our new model versus the observed data.

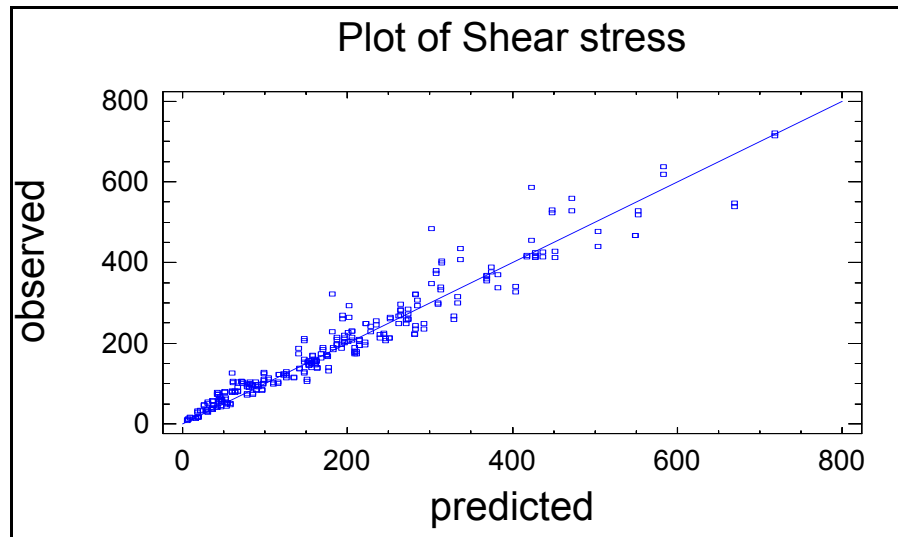


Figure 3.22 Observed data versus predicted values.

Figure 3.23 describes the measured curves and the predicted curves for the shear stress of the ETSEF20 with a particle concentration of 28% under various electric field strengths. The results show that the proposed empirical model may correctly predict the electrorheological property of the ETSEF fluids. It can directly provide a quantitative relationship (Equation 3.3) between the dynamic shear stress and the independent variables, except when working at low shear rates combined with a high electric field. This relationship can thus provide a reasonable explanation for the contributions of each independent variable to the viscosity and yield stress. Therefore, this model will be very useful for the development of ER fluids and their applications.

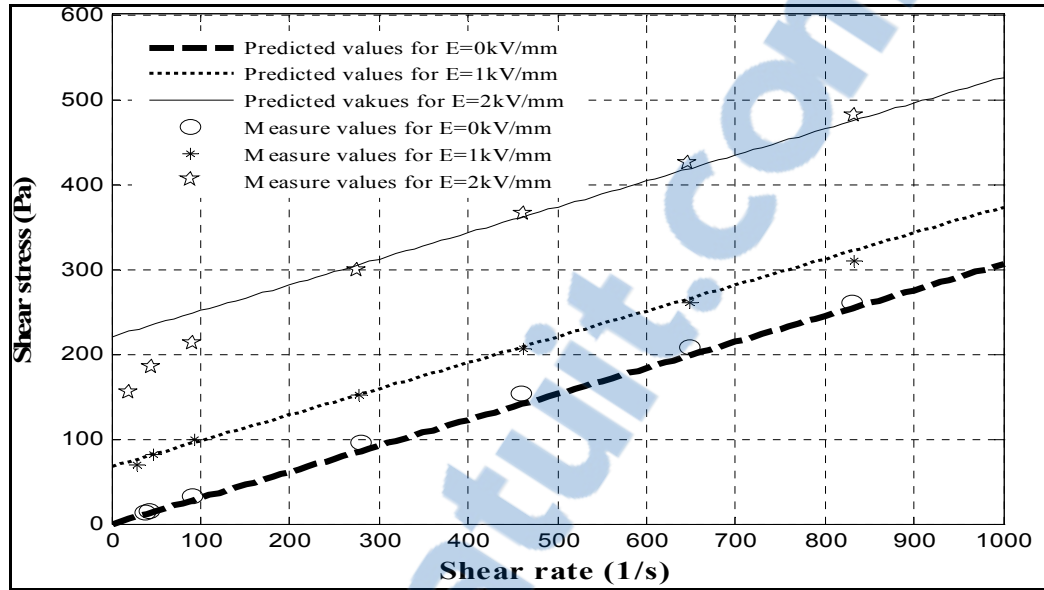


Figure 3.23 Predicted values vs. measured values for ETSEF20 with concentration of 28 Wt% under various electric field strengths.

Based on the Equation (3.2), the yield stress and the viscosity can be modeled as:

$$\tau_{yB} = 42.86E^2 + (0.895\phi^2 + 0.22\phi d - 37.83\phi + 369.67)E \quad (3.4)$$

$$\eta = 0.001(1.5\phi d - 0.12\phi^2 - 22d - 0.049\xi d + 1.1\xi) \quad (3.5)$$

where τ_{yB} is the yield stress and η is the dynamic viscosity.

It can be seen that the surfactant affects only the viscosity and not the yield stress, the surfactant thus has no a significant effect on ER efficiency. Figure 3.23 shows that the error of the predicted shear stress increases at low shear rates when the applied electric field increases.

3.4.2 A new Quasi-Bingham Model

The Bingham empiric model is suitable for describing ER behaviour at high shear rates, but it fails when modeling the ER fluid rheology at very low shear rates. Many studies indicate that

most ER fluids exhibit yield stress and shear-thinning properties. When the electric field is removed, they present a Newtonian behaviour or a weak pseudoplastic behaviour. Nevertheless, when an electric field is applied, they present strong pseudoplastic behaviours which are often accompanied by a static yield stress. This is due to the fact that the suspension microstructure depends on the relationship between the rate of the formation of particle links and the rate of breakdown by shear effects. Cross [35] proposed a suitable four-parameter equation (3.6) to describe the pseudoplastic behaviour of suspensions whose viscosity depends on the shear rate.

$$\tau = \eta_{\infty} \dot{\gamma} + (\eta_0 - \eta_{\infty}) \frac{\dot{\gamma}}{1 + (t\dot{\gamma})^n} \quad (3.6)$$

Unfortunately, this equation (3.6) could not describe the behavior of the pre-yield stress of ER fluids under a relative high electric field.

The results of our experimental design reveal that the dependence of shear stresses on the independent variables (electric field, shear rate, particle concentration and particle size etc.) is non-linear. Based on the Cross equation and the results obtained from the ANOVA analysis, we propose a new empirical model as shown in equation (3.7), which is named the Quasi-Bingham model.

$$\begin{aligned} \tau &= \tau_{yQB} + \eta_{\infty} \dot{\gamma} \quad \text{or} \quad \tau = \eta_{\infty} \dot{\gamma} & \text{when} \quad E &= 0 \\ \tau &= \tau_{yQB}(E) + \eta_0(E) \dot{\gamma} & \text{when} \quad E &\neq 0, \quad \dot{\gamma} \leq \dot{\gamma}_1 \\ \tau &= \tau_{yQB}(E) + \eta_{\infty} \dot{\gamma} + (\eta_0(E) - \eta_{\infty}) \frac{\dot{\gamma}}{1 + (t\dot{\gamma})^n} & \text{when} \quad E &\neq 0, \\ \tau &= \tau_{yQB}(E) + \eta_{\infty} \dot{\gamma} & \text{when} \quad E &\neq 0, \quad \dot{\gamma} \geq \dot{\gamma}_2 \end{aligned} \quad (3.7)$$

where, τ (E) is the shear stress (Pa), τ_{yQB} is the yield stress (Pa) in Quasi-Bingham, which is dependent on shear deformation, $\dot{\gamma}$ is the shear rate (1/s), η_0 is the zero shear viscosity, η_∞ is the infinite shear viscosity. The η_∞ has the same definition as the η in the equation (3.2).

The parameter "n" is known as the (Cross) Rate Constant; it is dimensionless and is a measure of the degree of the dependence of viscosity on the shear rate in the shear-thinning region, while the parameter "t" is known as the Cross time constant and has a dimension of time. Its reciprocal, $1/t$, gives us a critical shear rate that has been proven to be a useful indicator of the onset shear rate for shear thinning [35]. $\dot{\gamma}_1$ and $\dot{\gamma}_2$ are two additional critical shear rates.

We can obtain two relationships from the equations (3.7):

$$\begin{aligned} 1 + (t\dot{\gamma}_1)^n &\approx 1 \\ \dot{\gamma}_2 &\gg 1/t \end{aligned} \quad (3.8)$$

The values of τ_{yQB} , η_0 , η_∞ , t and n in equation (3.7) depend on the characteristics of electrorheological fluids when the electric field strength applied. In order to compute all these parameters, two assumptions are proposed in this paper:

- The infinite viscosity of the ER fluid has approximated values under different electric fields;
- According to the dielectric loss model of T. Hao [36], the yield stress τ_{yQB} is a function of E^2 .

These parameters above can be determined from experimental tests. Table 3.3 presents the fitting values for the ETSERF with different compositions. Table 3.3 shows that the yield stress (τ_{yQB}) is a function of the electric field strength and particle size, and the zero shear viscosity (η_0) is a function of the electric field strength, the particle size, and the particle mass concentration, i.e.:

$$\begin{aligned}\tau_{yQB} &= f(E^2, d) \\ \eta_0 &= f(E, d, \phi)\end{aligned}\tag{3.9}$$

Table 3.3 Fitting values of τ_{yQB} , η_0 , η_∞ , t and n

ER fluid	E (kV/mm)	t	n	τ_{yQB}	η_0	η_∞	$\eta_0 - \eta_\infty$	S	R ²
ETSERF40 $\phi=23$	0	0.064	1	0.0	1.36	0.36	1.00	445.8	0.9946
	1	0.059	1	11.2	4.18	0.30	3.88	3.7	0.9999
	2	0.049	1	44.9	8.71	0.31	8.40	49.1	0.9995
ETSERF20 $\phi=23$	0	0.031	1	0.0	0.22	0.18	0.04	0.44	1.000
	1	0.18	1	11.2	5.95	0.17	5.78	0.90	1.000
	2	0.071	1	44.0	6.52	0.21	6.31	7.95	0.9998
ETSERF40 $\phi=28$	0	0.014	1	0.0	1.72	0.70	1.02	1357.9	0.9962
	1	0.002	1	26.5	16.94	0.57	16.37	59.97	0.9997
	2	0.002	1	98.9	67.28	0.64	66.64	246.88	0.9985
ETSERF20 $\phi=28$	0	0.017	1	0.0	0.48	0.31	0.17	187.87	0.9971
	1	0.086	1	20.5	5.30	0.28	5.02	32.64	0.9994
	2	0.05	1	80.6	6.97	0.33	6.64	82.04	0.9991

We may notice that the shear stress depends not only on the shear rate, the electric field, the particle concentration, and the particle size, but also on the interactions of these parameters. The coefficients of determination R^2 indicate that the model accounts for 99% of the variability in the shear stress. The viscosity η_∞ and the yield stress are 0.3315 Pa.s and 80.6 Pa, respectively for the ETSERF20, with a 28% particle concentration under 2kV/mm of

electric field. The viscosity values from both the empirical and experimental models are very similar. Furthermore, the yield stress values obtained from the new Quasi-Bingham model are more accurate. In fact, according to recent research studies, it is difficult to obtain an accurate yield stress value from experiments. We can thus say that the Quasi-Bingham empirical expression is very appropriate for describing the dynamic behaviors of ER fluids, and the model is suitable for all ER fluids with shear-thinning behaviors.

3.5 Conclusion

The ANOVA analysis is a useful tool for characterizing ER fluids and developing an empirical model for predicting a variable dependent on multiple parameters. The experimental design method is a powerful tool for analyzing the interactions between parameters that cannot be revealed by examining one parameter at a time. The results of an experimental design developed on 288 shear stress measurements, applied to a new ER fluid called ETSERF and based on diatomite powders, are described in this paper. This home-made ER fluid was chosen because it manifests good electrorheological performances versus five other mixtures. The experimental results show that the shear stress increases with particle concentration, particle size, and electric field increases in the studied range.

Based on the Bingham model, two empirical models for the ETSERF rheology have been developed, which allow us to predict the yield stress and dynamic viscosity, respectively. The viscosity values from both the empirical models and experimental measurements are very similar, except at low shear rates.

A new Quasi-Bingham model has thus been developed from empirical experiments to describe ER shear-thinning behaviors, especially at low shear rates. The new model represents an improvement over the Bingham model, with very good coefficients of determination. The yield stress values from the Quasi-Bingham model are more accurate than those from the classical Bingham model.

The main findings are summarized as follows:

I. **Mass concentration:** In order to avoid saturation of the mixture, the mass concentration of particles must not exceed a given value which was found to be around 28% for the ETSERF. If a high mass concentration is combined with large particles, the increase in shear stress is more pronounced when an electric field is applied, but the electric field strength must increase for the particle chains to be formed, and significant ER effect produced.

II. **Electric field:** It is obvious that the electric field is an important and necessary factor for ER fluids. As expected, the shear stress increases with increases in the electric field following a 2-order polynomial function. Specifically, with the ER fluid composed of high particle mass concentrations and large particles, the shear stress is more significant. However, the electric field must be greater than a threshold value (1kV/mm) for good ER efficiency to be obtained. This is particularly important when using an ER fluid with a high particle concentration under a high shear rate. When a surfactant is added to the ER fluid having a high mass concentration and large particles, the shear stress has a small negative effect under a relative high electric field. The frequency of the electric field must be kept between the DC value and 10 Hz in order to obtain a high dielectric constant. It is possible to control the shear stress of the ER fluid by varying the electric field frequency between 10 and 100 Hz.

III. **Shear rate:** As expected, the shear stress increases along with the shear rate. At a high shear rate, the electric field strength must increase for the particles chains to be formed and a significant ER effect obtained.

IV. **Particle size and shape:** The particle size and shape are other very important factors which influence the properties of ER fluids. The shear stress increases with an increase in the particle size. The ETSERF20 produces a smaller ER effect than the ETSERF40 (with the same particle mass concentration). Specifically, when the fluid is composed of high uncrunched particles, the increase in shear stress is more significant with the electric field

applied. However, this efficiency can be reduced if a surfactant is used. When adding a surfactant to an ER fluid with uncrunched particles, the surfactant produces a negative ER effect when the particle concentration, the electric field strength, or the shear rate is relatively high.

V. **Surfactant:** The surfactant must be introduced in order to slow down the sedimentation of particles in the ER fluid. However, using a surfactant is not beneficial for the shear stress, especially when large particles are used; any adverse effect produced is not that significant though, and it is recommended that it be used. Furthermore, the ER effect of the surfactant is beneficial for ER fluids with small particles, and is only negative when uncrunched particles are used under a relatively high electric field.

3.6 Acknowledgment

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CHAPITRE 4

ARTICLE #2 «EXPERIMENTAL INVESTIGATION OF DIELECTRIC PROPERTIES ON ELECTORRHEOLOGICAL FLUIDS»

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Résumé

Afin de pouvoir comprendre la performance de nos fluides ER, nous avons étudié expérimentalement leurs propriétés diélectriques en comparaison avec leurs propriétés ER. Les études indiquent que la performance ER est un résultat des forces de la polarisation électrique. Les interactions électrostatiques entre les dipôles polarisés créent des chaînes qui sont alignées avec le champ électrique appliqué, et par conséquent, la viscosité apparente de la suspension augmente, particulièrement à basse vitesse de cisaillement. Les arrangements linéaires des particules sont détruits à haute vitesse de cisaillement, car il n'y a pas suffisamment de temps pour reformer les chaînes, donc la viscosité apparente approche la valeur sans champ électrique. Beaucoup d'articles qui présentent des calculs théoriques et des simulations numériques, basés sur le modèle diélectrique ou le modèle de la conduction, ont été publiés. Cependant, il est impossible de pouvoir expliquer certains effets en utilisant ce genre de modèles. Par exemple, l'effet de l'eau, un matériel possédant une grande constante diélectrique, donne un faible effet ER. Il est essentiel que la conductivité et la constante diélectrique qui gouvernent leurs performances ER puissent être optimisées sous certaines conditions. Un système hétérogène possède quatre mécanismes possibles de polarisation tels que : polarisation électronique, atomique, dipolaire et interfaciale (Maxwell-Wagner). La détermination du type de polarisation dans un fluide ER sous un champ

électrique est très importante pour comprendre l'effet ER du fluide ER. Le but principal de cet article est d'expliquer les observations expérimentales. Les propriétés diélectriques des composites ont été analysées afin de déterminer quel type de polarisation domine pour expliquer l'effet ER. D'autre part, il n'existe pas de modèle simple qui peut expliquer tous les comportements statiques et dynamiques d'un fluide ER, particulièrement quand la géométrie des particules est irrégulière. Donc, l'efficacité ER de différents fluides ER est comparée et la dépendance de la constante diélectrique, de la perte diélectrique et du temps de relaxation du fluide ER sont reliées à la taille de particules, à la concentration des particules, à l'humidité et à l'addition d'un surfactant. L'influence du temps de relaxation sur l'effet ER est étudiée particulièrement en observant le vieillissement d'un fluide ER. Il est évident que nos résultats nous aident à mieux comprendre le mécanisme ER et aident à la conception d'un fluide ER à haute performance.

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Abstract

A home-made electrorheological fluid, known as ETSERF, has been created with suspension-based powders dispersed in silicon oil. Because of the special structure of their particles, ETSERF suspensions present a complex behaviour. In absence of electric field, the ETSERF fluid manifests a near Newtonian behaviour, but when the electric field is applied, it exhibits a pseudoplastic behaviour with yield stress. The ER effect under DC electric fields has been experimentally investigated using both hydrous and anhydrous ER fluids. ER properties are strongly dependent on the dielectric properties of ETSERF suspensions and hydrous ER fluids have a high dielectric constant and a high relaxation frequency which show a strong electrorheological effect. The relationship between the electrorheological effect and the permittivity of ER fluids has also been extensively studied. Experimental results show that the interfacial polarization plays an important role in the electrorheological phenomenon. The ageing of ETSERF fluids was also studied and it was found that the dielectric properties (mainly the dielectric loss tangent) and ER properties are strongly related to the duration of ageing. A fresh ETSERF suspension exhibits high relaxation frequency and high dielectric constant. These results are mainly explained by the effect of interfacial polarizations.

Keywords: Electrorheological fluid, pseudoplastic, permittivity, relaxation, interfacial polarization, ageing.

4.1 Introduction

Over the last two decades, electrorheological (ER) fluids have fascinated many scientists, engineers and inventors. The ER phenomenon was first described by Winslow in 1949 [1]. The ER fluids are notably characterized by a high shear stress and a fast response time. Their properties [2-4] are related to important factors such as shear rate, electric field, electric field frequency, fluid composition, temperature, addition of additives, etc. The ER fluids can potentially be applied in many industrial areas. They may be used to control vibration [3-5] and damping [6] through the application of high electric fields in real time. However, the presence of many technical problems such as particle sedimentation, fluid heating [7], etc., limits the number of industrial applications using ER fluids [8, 9]. In addition, the ER devices require high voltages to supply very high electric fields. Their rheological behaviour is complex and non-linear and their mechanism of action is not very well understood. Researchers are presently trying to develop ER fluid technologies [10, 11] that can overcome these problems. However, the performances of ER fluids depend not only on the mixture, but also on many other factors, such as shear rate, electric field, electric field frequency [12-14], humidity, temperature, particle concentration [15, 16], particle size, particle geometry [17], density ratio between the particles and the base liquid, surfactant effect [18, 19], etc. The ER behaviour is a result of electric polarization forces. Under an electric field, the electrostatic interaction between the induced dipoles creates particle clusters aligned with the electric field and, consequently the apparent viscosity of the suspension especially at low shear rates increases. The particle arrangement is destroyed at higher shear rates, and the chains formation can not be reformed, therefore the apparent viscosity approaches to the value for field-off state. Numerous papers have recently been published presenting theoretical calculations and computer simulations based on the dielectric model or conduction model [20-27]. According to the bulk polarization theory [28], the main factor controlling the particle polarizability is the permittivity of dispersed material. However, a little modification of the particle surface which influences the bulk particle permittivity may play an important role in the ER phenomenon. Thus, a small amount of water [29-31] or another polar compound (alcohol, ethylene glycol, dimethylformamide) [2] absorbed on the surface of

particles induces the ER behaviour for many materials excepted for semiconducting polymer-based suspensions [32]. Water absorbed onto the particulate phase has been observed to dramatically enhance the performance of fluids compared to ‘dry’ particles at comparable electric fields. However, because of the limit of the temperature, device corrosion, water evaporation and dispersion instability, certain ‘dry’ ER fluids were developed and were analyzed via the dielectric properties [33-35]. Essentially, the conductivity and dielectric constant of ER materials have governing their ER performance which may be maximized under an optimum set of conditions [36]. Some researchers have shown that the yield stress does not change monotonically with the dielectric constant or the dielectric loss tangent even for the same series of samples [37]. The study of Sung and al indicates that the fast relaxation time of PANI/TiO₂ hybrid was considered to enhance electrostatic force over shear force under a hydrodynamic flow, showing its improved ER performance [38]. According to recent researches, the polarization controls the ER effect when it is introduced by an external electric field. However, a heterogeneous system could exhibit four kinds of polarizations: electronic, atomic, Debye and interfacial (Maxwell-Wagner), which may have a predominant effect on ER fluid efficiency. The dielectric properties of particle-matrix composites are analyzed. From the experiments, we may determine which type of polarization is dominant for explaining ER effect.

There is no simple model which can explain all the steady and dynamic physical properties of ER fluids, particularly, when the geometries of the particles are irregular. In this paper, the ER behaviour of various ER fluids are compared and the dependence of the dielectric constant, dielectric loss and relaxation time of the ER fluids on particle size, particle concentration, humidity and addition of the surfactant are experimentally studied. Particularly, the influence of the relaxation time on electrorheological effect is studied via the observations of ageing of ER fluids. Our results help further understand the ER mechanism and also offer a clear explication on how to design high performance ER fluids.

4.2 Experimentation

The ER fluids are composed of home-made small solid particles suspended in silicone oil. The average sizes of particles are approximately 20 μm and 40 μm and the home-made fluids are called ETSERF20 and ETSERF40, respectively. Two mass ratios, 23% and 28%, were selected. The particles were prepared in two states: moist or dry. The ETSERF is a mixture with diatomite particles which are immersed into silicone oil with a surfactant TWEEN 80 (Polyethylene glycol sorbitan monooleate). The diatomite powder was selected because of its honeycomb structure. The particles were dried under 180 °C for two hours in order to prepare ER fluids. The shear stress measurement of the ER fluid is carried out by a cylindrical rotary viscometer (Couette). This viscometer was designed and manufactured according to ISO 3219 [39]. It combines a speed control system and an amplifier/supply high-voltage system (10 kV) in order to perform an automatic measurement of the rheogram: shear stress versus shear rate. The investigated fluid is filled between two coaxial cylinders and the shearing laminar motion of ER fluid is obtained through the rotation of the inner cylinder, which may have various uniform rotational speeds. The outer cylinder is free to rotate in order to measure the tangential force. This force is applied on a flexible beam instrumented. The shear stress is then computed from the strain gauge signal. Dielectric properties were measured by a Novocontrol broadband dielectric spectrometer inside a frequency range of 10^{-1} to 10^5 Hz. The dielectric permittivity of the ETSERF fluid was measured at 23°C according to standard test methods [40]. In order to determine the polarisable mechanisms of ER fluids, the particle-matrix composites were also measured and PMMA was selected for the matrix.

4.3 Basic concepts

4.3.1 Polarization mechanism of heterogeneous dielectrics

The complex dielectric constant ϵ^* and the loss tangent η are usually written as [41]:

$$\epsilon^* = \epsilon' - i\epsilon'' = \epsilon'(1 - i \tan \delta_e) \quad (4.1)$$

where ϵ' , ϵ'' are the dielectric real part, the dielectric imaginary part and $\tan\delta_e$ the dielectric loss factor (or loss tangent), respectively.

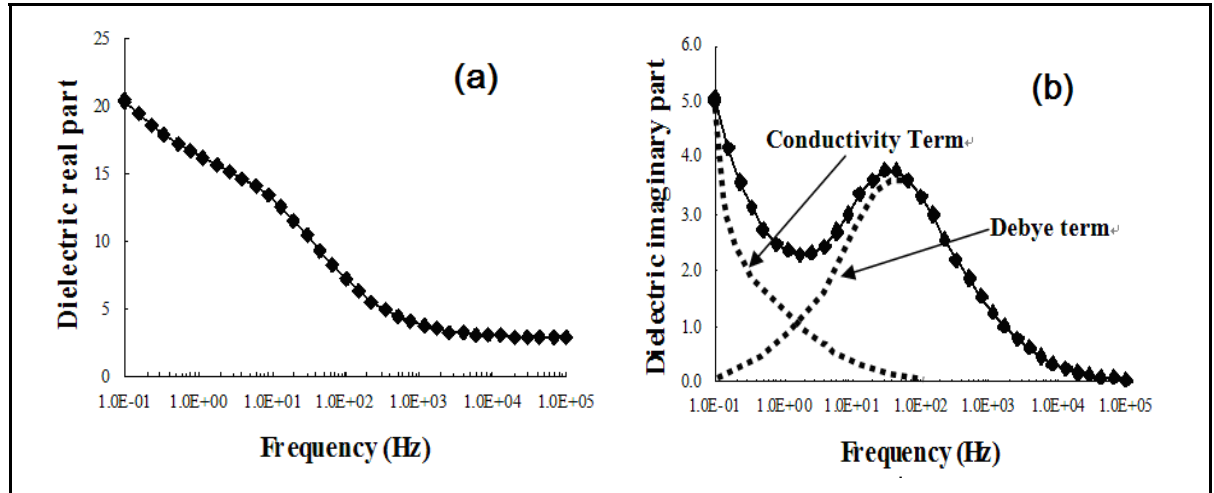


Figure 4.1 Relaxation spectrum of the ETSERF40 ER fluid.

Different types of polarization mechanisms are found in a heterogeneous system, they are electronic, atomic, dipole (Debye) and interfacial polarization. Usually, the electronic and atomic polarizations are classified as fast polarizations while the Debye and interfacial polarizations are classified as slow polarizations. For the fast polarizations, the response time is about 10^{-16} to 10^{-12} seconds while it is higher than 10^{-10} seconds for slow polarizations. According to recent research studies, the interfacial polarization should be responsible of ER effect for most of the materials studied [42]. We will therefore focus mainly on the effect of the interfacial polarization for the ER fluids considered in this study. Interfacial polarization is mainly explained by a local accumulation of charges [43]. In the case of ER fluids, most of dielectric phenomena occur at the particle surfaces. For example, if the particles are hydrophobic, the local conductivity is modified due to the accumulation of charges at surfaces. Therefore, when an electric field is applied, the interfacial polarization is observed. For some materials, the dielectric response of the composite materials is mostly important at low frequencies. The relaxation spectrum of ETSERF40 which contains no surfactant and water at ambient temperature is shown in Figure 4.1.

It is observed that both parts of complex dielectric constants, real and imaginary, are increased at low frequencies. If we assume that the dielectric imaginary part are the superposition of two parts: one part is the ‘Debye’ term, one is conductivity term like in figure 4.1 (b), and we can approximately explain the dielectric properties of ER fluids by using Maxwell-Wagner equation.

4.3.2 Theories of the slow polarization

Debye theory

The equation (4.2) is known as Debye equation and it describe the behavior of polar dielectrics at various frequencies.

$$\epsilon^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + i\omega\tau_0} = \left(\epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (\omega\tau_0)^2} \right) - i \left(\frac{(\epsilon_s - \epsilon_\infty)\omega\tau_0}{1 + (\omega\tau_0)^2} \right) \quad (4.2)$$

Maxwell-Wagner equation

The simplest model to calculate the complex permittivity which is produced by the interfacial polarization is the Maxwell-Wagner model (equations 4.3 to 4.5).

$$\epsilon^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + i\omega\tau_0} - i \frac{\sigma_{dc}}{\omega\epsilon_0} = \left(\epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (\omega\tau_0)^2} \right) - i \left(\frac{\sigma_{dc}}{\omega\epsilon_0} + \frac{(\epsilon_s - \epsilon_\infty)\omega\tau_0}{1 + (\omega\tau_0)^2} \right) \quad (4.3)$$

$$\epsilon' = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (\omega\tau_0)^2} \quad (4.4)$$

$$\epsilon'' = \frac{\sigma_{dc}}{\omega\epsilon_0} + \frac{(\epsilon_s - \epsilon_\infty)\omega\tau_0}{1 + (\omega\tau_0)^2} \quad (4.5)$$

where ϵ_∞ represents the value of the permittivity when the frequency is infinite; ϵ_s represents the value of the permittivity when the frequency is zero; σ_{dc} is direct current conductivity; ω , τ_0 are respectively the frequency and the relaxation time and ϵ_0 designates the dielectric constant of vacuum.

4.3.3 The dependence on Relaxation of the ER effect

The relaxation frequency is defined by a local peak of dielectric imaginary part. Block et al [44] indicated the relaxation frequency was very important for ER fluid because the relaxation frequency of ER fluid was proportional to the rate of polarization of ER fluid, but if the polarization rate is too high or too low, the good ER effect can not be obtained. For obtaining a good ERF effect, the relaxation frequency must be in the range 10^2 to 10^5 Hz and the difference of the dielectric constant below and above the relaxation frequency must be large. If the frequency bandwidth is defined as the two frequencies at which there is a minimum dielectric imaginary part surrounding the peak, then the difference in the amplitudes of dielectric real part found within the frequency bandwidth must be large [45]. This suggests that the ER effect may be correlated with the particles dielectric loss, because the particles move within the particles as charges move under an electric field. These motions would be one of the causes of dielectric loss [42]. Usually, the dielectric imaginary part can be explained by two terms: the Debye and conductivity. The Maxwell-Wagner equation is often used with success for describing the behavior related to frequency [43]. If we consider using the theory of Dissado-Hill combined with the Maxwell-Wagner equation, we can thus obtain a good explanation. The Cluster approach of Dissado-Hill [46] is based on a comprehensive model of physical structures represented by an imperfectly ordered state and its consequences for the dynamics of constituent molecules. This model assumes that the condensed substance is composed of spatially limited regions which have a partially regular structural order of individual units. These special regions are called clusters. The Dissado-Hill theory takes into account the many-body interactions that exist between clusters. Based on the cluster model, Dissado-Hill proposed two theories, one for dipolar relaxation, and the other for the QDC (Quasi-DC) conduction process. For the dipolar case, the dipoles are not independent as they

are in the Debye model. Two kinds of interactions, which can be represented as intra-cluster motions and inter-cluster exchanges, are observed. Each of these processes will produce its own characteristic contribution to the final susceptibility function. First, the dipoles relaxation process is predicted by the Debye model. This motion may be assumed to result from the Debye polarization under the electric field. At the same time, the dipoles near the edge of the cluster interconnect with their neighboring cluster. This effect will affect the field of dipoles and therefore the overall effect will be an interaction between a process with an exponential single dipole relaxation of the form $e^{-t/\tau}$ and a concomitant t^{-n} behavior for the relaxation of a cluster dipole moment. Because the motions of dipoles at the interconnection between the neighboring clusters are behind the inter-cluster exchange, the relaxation of cluster dipole moments will have a polarization time greater than in the intra-cluster motion [47]. The particles dispersed in the ER fluid can be considered as clusters. When the electric field is applied, two principal processes occur simultaneously: one is the polarization of molecules, such as the Debye polarization (intra-cluster motion) and the other is the interfacial polarization between clusters. Of course, these two processes are not completely independent as it is assumed in the cluster approach of Dissado-Hill. The question therefore becomes: which of these two processes has the most significant influence on the ER effect, according to the fluid mixture. In order to determine whether the Dipole or Maxwell-Wagner polarizations contribute to the ER effect, we measured the dielectric properties of moist and dry particles/silicone oil. However, considering only these two tests is not enough because their dispersions appear in close frequency ranges. By adding the measurement of the interfacial polarization due to the dielectric constants and the conductivities of the fluid and particles, we observed the dependence of the ageing of ER suspensions on their dielectric properties. Furthermore, we observed the dielectric permittivity of particles-mixture composites in determining the polarization mechanism of ER. According to these results, it was possible to demonstrate that the ER effect of ETSEF is based on the Maxwell-Wagner polarization.

4.4 Results and discussions

The ER system is a dielectric mixture and its electrical properties are wholly determined by the properties of its constituents and their interactions. In this paper, the dielectric permittivity of ER fluids is observed by considering different particle concentrations, different particle sizes, dry or moist particles, with or without surfactants. It is observed that all these parameters strongly influence the dielectric properties, and consequently, their ER behaviour. The relationship between the ER effect and the relaxation frequency will now be discussed.

4.4.1 ER effect

Figure 4.2 (a) and (b) show the effect of particle concentrations, sizes and shear rates on the ER effect.

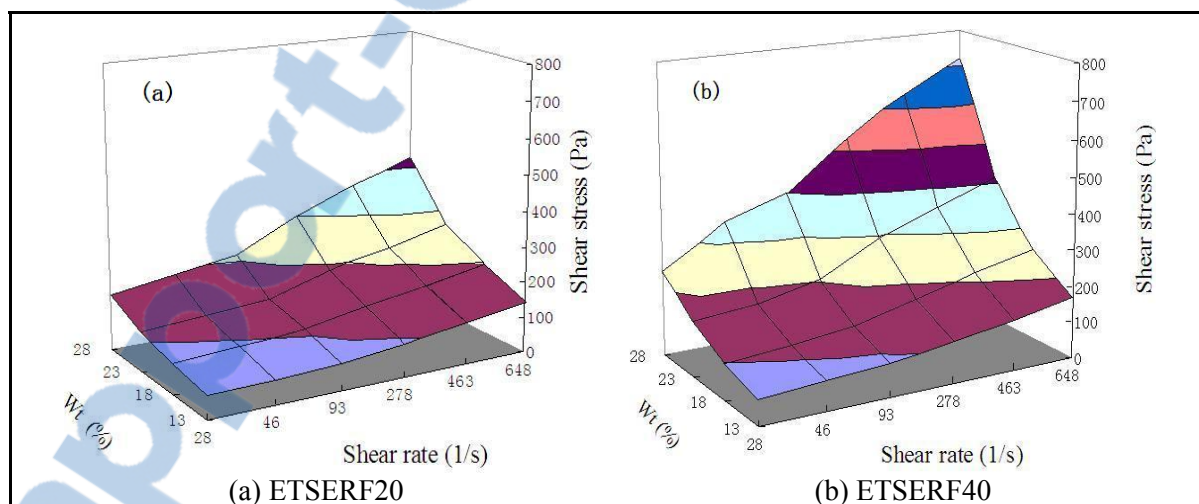


Figure 4.2 Dependence of shear stress on particle concentration and size under $E=2\text{kV/mm}$.

An electric field of 2kV/mm was applied to the ETSEF not containing surfactant. It can be seen that the shear stress increases for all fluids with shear rate and concentration (in the con-

sidered range) when a high electric field strength is applied. This effect is more pronounced for large particles (Figure 4.2 (b)). Figure 4.3 (a) and (b) show similar results for the ET-SERF though it contains surfactants.

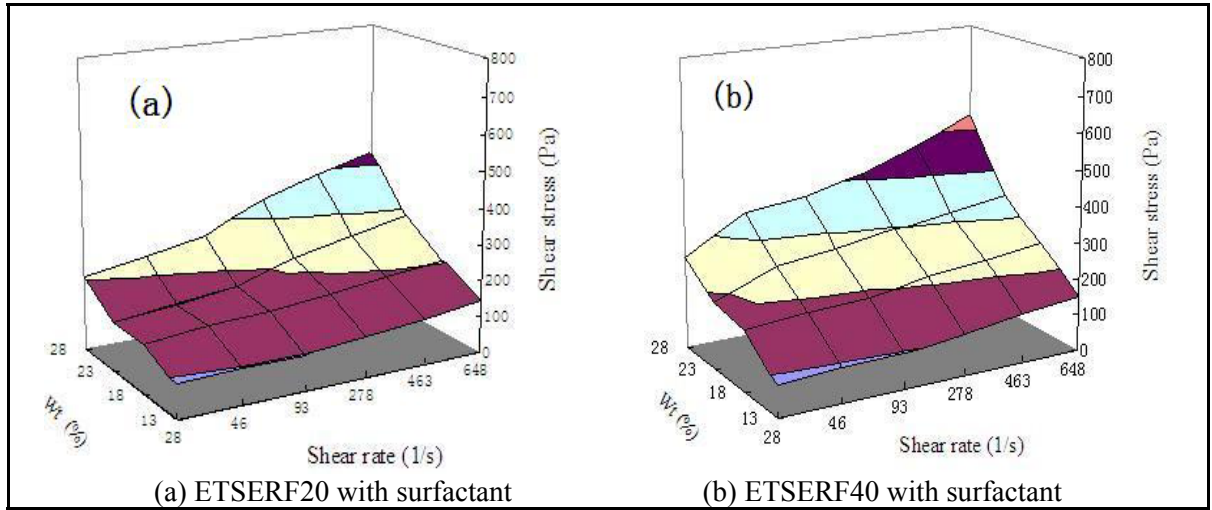


Figure 4.3 Dependence of shear stress on particle concentration and size with surfactant under $E=2\text{kV/mm}$.

By comparing figure 4.2 and 4.3, even if the introduction of surfactant reduces the efficiency of ET-SERF40 at high shear rate and high mass concentration, it can be assumed that this prejudicial effect is not significant enough and consequently it may be included in the design of ET-SERF for slowing its sedimentation. In Figure 4.4 (a), (b) and (c), the rheological curves of the ET-SERF show the effect of dry and moist particles under different electric fields. The ET-SERF with moist particles exhibits a better ER efficiency with shear rate. The effect of humidity is more significant with the electric field. However, the humidity has no effect when the electric field is not applied. From above rheological results of ER fluids, it is observed that an ET-SERF fluid manifests a near-Newtonian behaviour under the absence of an electric field, but it exhibits a pseudo-plastic behaviour with yield stress when an electric field is applied.

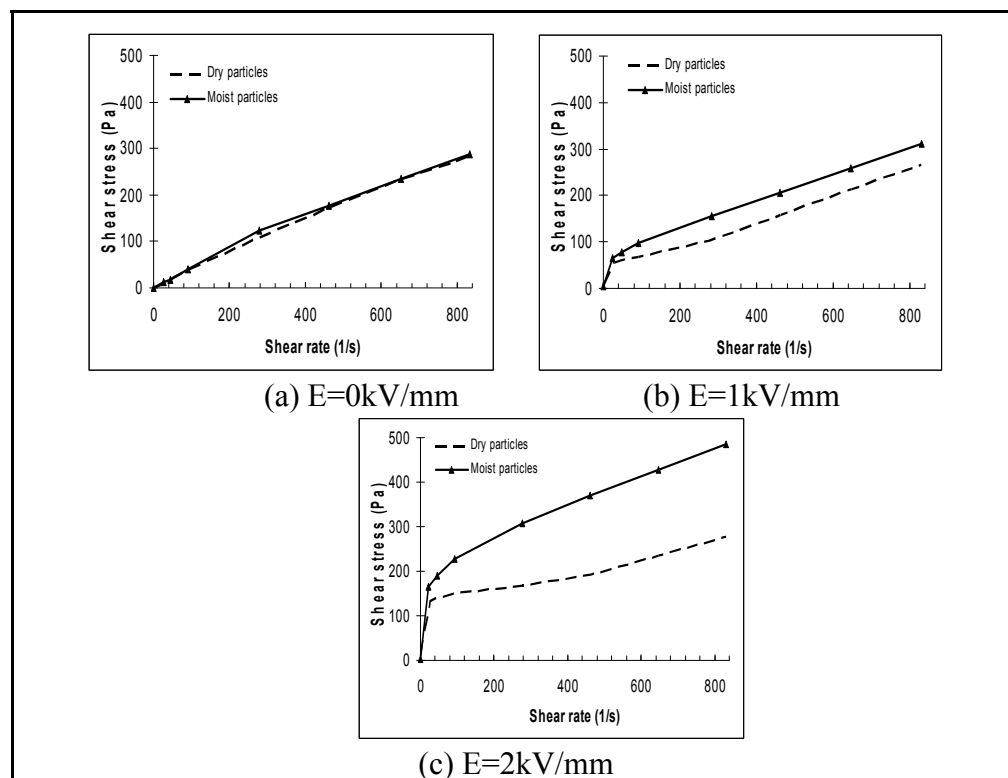


Figure 4.4 The effects of humidity on ER behavior of ER fluids under different electric fields.

4.4.2 The dielectric properties of ER suspensions

4.4.2.1 Influence of particle sizes, particle concentrations and surfactant on dielectric properties of ER suspension

The permittivity of the ETSERF was measured without surfactant and with surfactant, with two mass concentrations (23 and 28%) and two particle sizes (20 and 40 μm). The results are shown in Figure 4.5, 4.6 and 4.7. The permittivity curves of ETSERF20 and ETSERF40 with a mass concentration of 23% are shown in Figure 4.5. From Figure 4.5 (a), the dependences of particle size on the dielectric behavior are clearly observed. The dielectric real part of ER fluids increases with the particle size, especially at low frequencies. The dielectric loss tangent is shown in Figure 4.5 (b). The ER fluid with large particles exhibits high values $\tan\delta_e$ and its relaxation frequency is lower comparing with the ER fluid made of small size

particles. This implies that the ER fluids using large particles will dissipate more power when it is polarized. The permittivity of ETSERF20 and ETSETF40 with surfactant using the same mass concentration is shown in figure 4.6. Comparing with Figure 4.5, we can notice that the dielectric parameters decrease a little bit with addition of surfactant, but the difference is not enough significant to avoid it and it is recommended to use it for slowing the sedimentation.

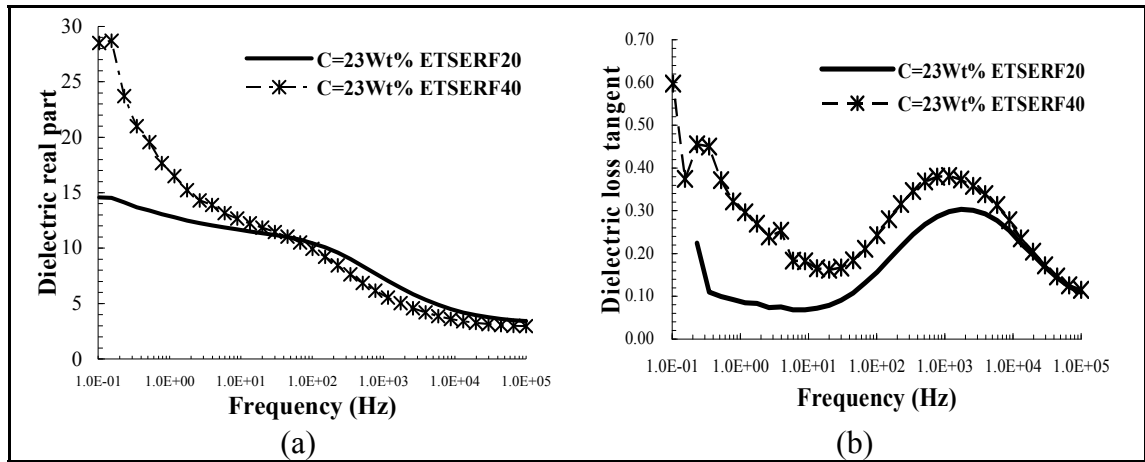


Figure 4.5 Influence of particle sizes on the dielectric proprieties of ETSERF with no surfactant.

Figure 4.7 shows the results of the dielectric properties under different mass concentrations for the ER fluids made with dry particles. It can be observed that the dielectric constant is dependent on the particle concentrations. The dielectric constant significantly increases with an increase in the particle concentration at low frequencies. The relaxation frequency, observed from the peak in Figure 4.7(b), also changes with the particle concentrations. The effect of particles on the conductivity is very significant. Based on these observations, a high particle concentration (in the considered range) is recommended for designing the ETSERF.

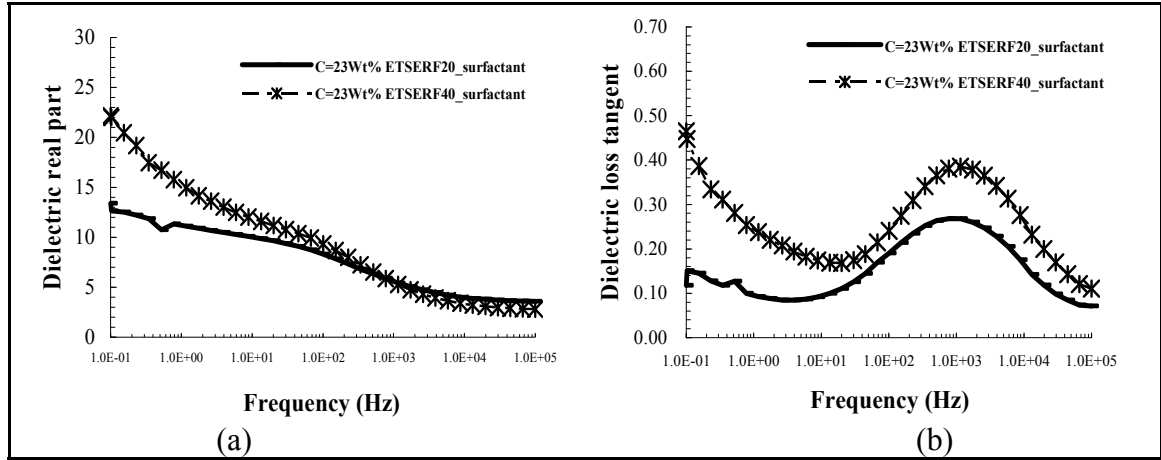


Figure 4.6 Influence of particle sizes on the dielectric properties of ETSERF with surfactant.

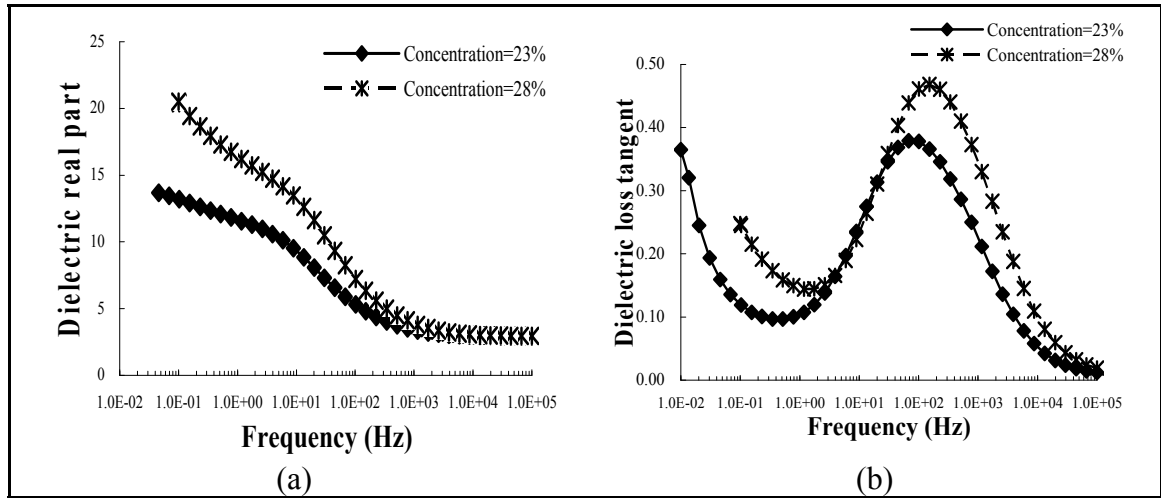


Figure 4.7 The effect of particle concentrations on the dielectric properties of ER fluid.

In summary, these results show that the complex dielectric constants of ER fluids are dependent on the particle concentration, the particle size and the addition of surfactants, especially at low frequencies. From the results observed, the dielectric constant, the dielectric loss factor and the conduction all affect the ER performance. These results suggest that better ER performances will be obtained with low frequencies or DC electric fields.

4.4.2.2 Influence of humidity on dielectric properties of ER suspension

Figure 4.8 shows the permittivity for ER fluids made with moist and dry particles, respectively. The effect of humidity of particles is very significant on the dielectric properties and an increase is observed in the dielectric constant. With moist particles, the relaxation frequency moves up to a relative high value and simultaneously, the conductivity increases very fast at low frequencies. All these characteristics will produce positive effects.

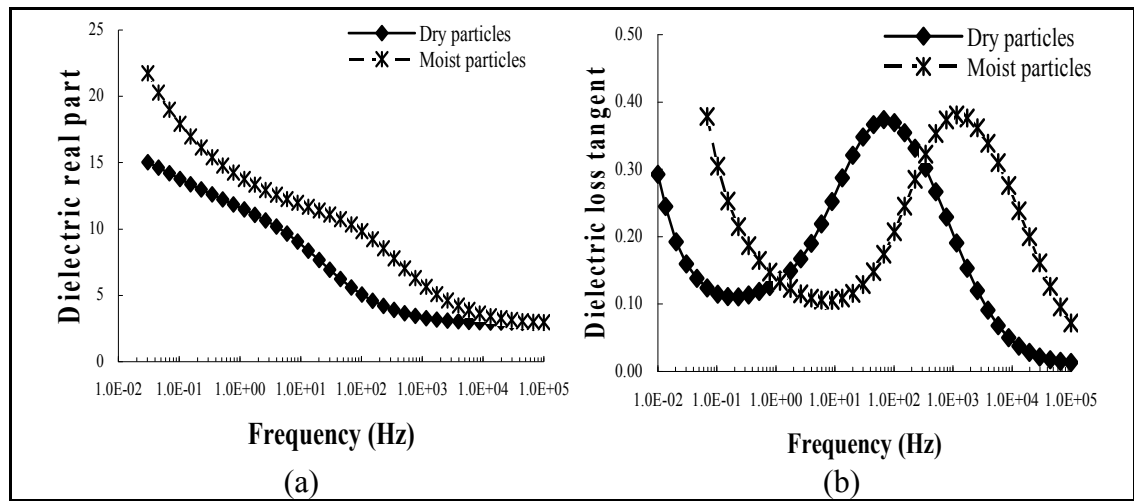


Figure 4.8 Comparison of dielectric properties for ER fluids with dry particles and moist particles with a concentration of 23%.

Another important factor is the conductivity of ER suspensions. In fact, the conductivity arises from imperfect particle structures or from humidity. Figures 4.6 to 4.8 show that the dielectric loss tangent increases at low frequencies. This result observed in the low frequency range does not agree with the Debye theory. If the Debye model is replaced by an explanation that combines the theory of Dissado-Hill with the Maxwell-Wagner equation, it then becomes possible to qualitatively explain these phenomena.

4.4.3 Polarization mechanisms in ER suspensions (Interfacial polarization)

In order to determine the polarizable mechanisms of ER fluids, the ETSEF40 particles are prepared as particle-matrix composites; PMMA was selected as a matrix. PMMA was selected as matrix because it can assure the mono-dispersity of ER particles [48, 49]. The dielectric properties of the particle-matrix composites were measured and the experimental results are described in Figure 4.9.

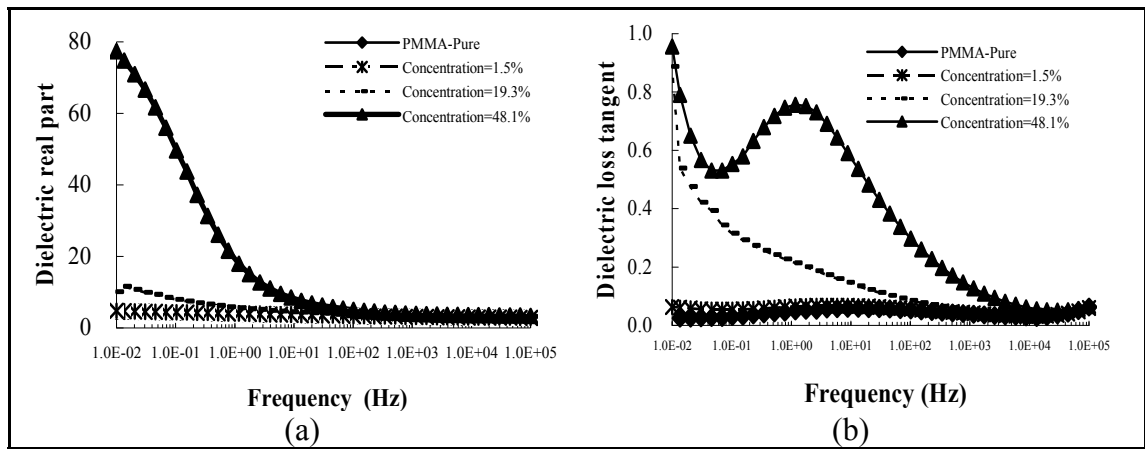


Figure 4.9 Relative constant and dielectric loss tangent for the particles-matrix.

It can be observed that the dielectric constant and dielectric loss tangent of mixtures are very low when the particle concentrations are very low (1.5 to 19.3 %). In this case, the relaxation peak is very difficult to identify. Although the loss tangent increases in the low frequency range by using a 19.3% mass concentration, only conductivity plays an important role. According to the theory of Dissado-Hill, the particles can be considered as clusters and then, they can not move or vary their orientation under the electric field. But when the particle concentration is relatively high (48.1%), a lot of surface charges of particles exchanges, and an interfacial polarization occurs, thus leading to a relaxation peak (Figure 4.9 (b)). These effects are due to the interfacial polarization that occurs at the boundaries separating the particles and matrix regions. As the frequency increases, the time available for the drift of charge carriers is reduced, and the observed increase in ϵ' and $\tan\delta_e$ is substantially affected.

At low frequencies, charge polarization at electrodes is also considered to be a contributing factor to the increase of dielectric constant and dielectric loss factor. These phenomena can be explained by the special form and large surface of considered ETSERF particles. The interfacial polarization plays a principal effect comparing with the three others kind of polarizations. The effects of interaction between the particles and interfacial polarization are very important for designing ER fluids.

4.4.4 The relation between the ageing of ETSERF and dielectric loss

The ER properties and the dielectric properties of an ETSERF40 suspension, based on a concentration of 23% with dry particles, were observed for more than 72 hours. Figure 4.10 shows the rheograms of ETSERF.

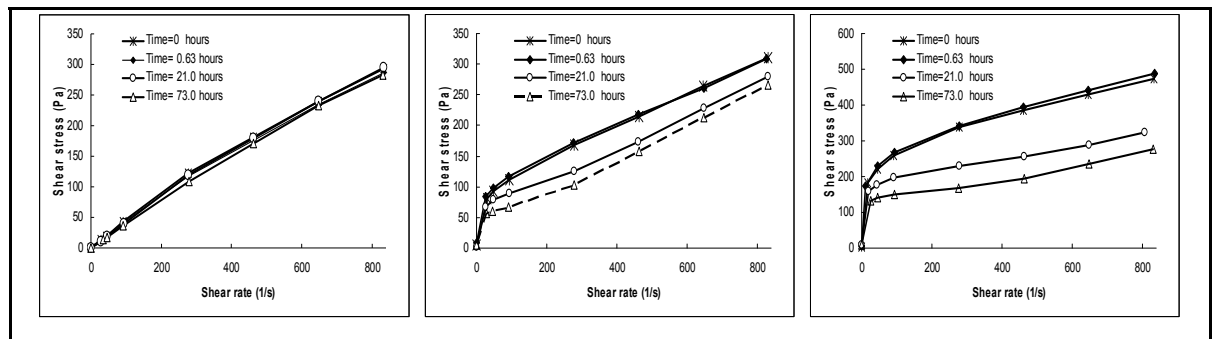


Figure 4.10 The observation of the ageing of ETSERF40 fluid.

It can be observed that duration has no effect on shear stress when electric field is not applied. However, this effect becomes significant when the electric field is applied, especially when it is relatively high (2 kV/mm). For example, the shear stress decreases from 394 Pa to 193 Pa at a shear rate of 462 (1/s) under 2 kV/mm. If we define this phenomenon as the ageing of ER fluids, the ER properties and the dielectric properties (mainly the dielectric loss factor) are seen to be strongly dependent on the duration of ageing. From Figure 4.11, it can be seen that the dielectric constant variations are important in the relaxation frequency range. On the other hand, the relaxation frequency decreases from 30 Hz to 0.2 Hz for an ageing

over 72 hours. In theory, the smaller the relaxation frequency, the slower the response for establishing a polarization is. Thus, the ER system needs a longer time to form particle chains. In shear mode, it will not have enough time to form chains, and therefore, the ER efficiency will be reduced. This ageing phenomenon may be due to the fact that particles agglomerate into bigger particles or because the particle structures change.

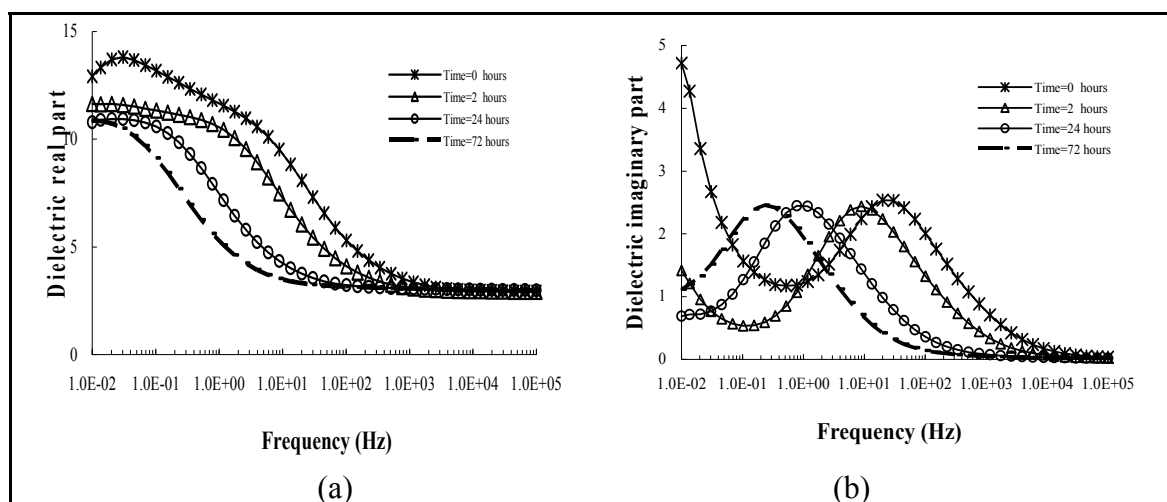


Figure 4.11 Dependence of dielectric properties on time for ETSERF with 23% concentration and dry particles.

4.5 Conclusion

Because of the special structure of dispersed particles, ETSERF suspensions present a complex behavior. In absence of electric field, the ETSERF fluid manifests a near Newtonian behavior, but the fluids exhibit a pseudo-plastic behavior with yield stress when the electric field is applied, especially for ETSERF40. The ETSERF efficiency is strongly dependent on dielectric properties and hydrous ER fluids have a high dielectric constant and a high relaxation frequency which show a strong electrorheological effect. It was explained that interfacial polarization contributes to the ER effect. The slow polarization is the preponderant effect and an efficient ER effect will appear in the low-frequency or D.C. range. Although the efficiency will be a little bit reduced, surfactant must be added in order to slow the

sedimentation. However, the dielectric properties and ER performance are strongly related to the duration of ageing. A fresh ETSEF suspension exhibits high relaxation frequency and high dielectric constant. These results are mainly explained by the effect of interfacial polarizations. The experimental results show that the complex dielectric constants of ER fluids are dependent on the particle concentration, the particle size and the addition of surfactants, especially at low frequencies. From the results observed, the dielectric constant, the dielectric loss factor and the conduction all affect the ER performance. The observation of the ageing of an ER fluid and of the dielectric of PMMA particle-matrix is a good method for distinguishing between the Debye polarization and the Maxwell-Wagner polarization. From experimental results, it is evident that the Debye dielectric relaxation cannot explain the dielectric phenomena of our ETSEF fluids and that the Cluster approach of Dissado-Hill may provide a better explanation of phenomena. By investigating the dielectric constant, the conductivity and the relaxation frequencies, the dielectric properties studies allowed for designing an efficient ETSEF fluid. It was shown that ER efficiency is increased by designing a fluid with moist and large particles, with a 28% mass concentration.

4.6 Acknowledgements

The authors gratefully acknowledge the financial support provided by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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CHAPITRE 5

ARTICLE #3 «CONTROL OF ROTOR TORSIONAL VIBRATIONS BY USING AN ELECTORRHEOLOGICAL FLUID DYNAMIC ABSORBER»

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This paper is accepted as an article to Journal of Vibration and Control (JVC), 37 pages.

Résumé

Le fonctionnement et la modélisation de fluide ER ont été étudiés dans les articles précédents (chapitres 3 et 4). Le contrôle des vibrations d'un système mécanique est un sujet important en pratique, d'une part à cause de ses applications et d'autre part à cause de la difficulté du contrôle des vibrations en torsion d'un rotor opérant à vitesse variable. Nous avons conçu un absorbeur qui utilise un fluide ER. Cet absorbeur est nommé 'smart ER dynamic absorber'. En comparaison avec un absorbeur dynamique normal, cet absorbeur est beaucoup plus contrôlable, particulièrement pour les systèmes dont la vitesse est variable. L'analyse théorique et la simulation d'absorption des vibrations ont été réalisées afin de comprendre l'effet du champ électrique. En mode cisaillement, l'amortissement et la rigidité sont variés quand le champ électrique est appliqué. Un modèle non-linéaire se fonde sur le modèle de Quasi-Bingham afin de décrire la performance dynamique du fluide ER. Les résultats expérimentaux montrent que cet absorbeur est efficace ce qui permet un bon contrôle des vibrations en torsion.

Cet article a été accepté par "Journal of vibration and control" et est présenté intégralement dans la section suivante.

Abstract

Torsional rotor vibrations are undesirable phenomena which are very difficult to control in rotating systems. A common method for reducing vibrations involves the use of dynamic absorbers. However, if their physical parameters are constant, the frequency range of efficiency of dynamic absorbers is tight, making them unsuitable for systems with variable speeds. The use of smart materials, due to their variable and controllable mechanical properties, may be a powerful tool for increasing the frequency range. Electrorheological (ER) fluids are attractive materials that undergo very fast reversible changes in their rheological properties upon the application of an electric field. In this study, an electrorheological dynamic torsional absorber, called the Smart ER Dynamic Absorber (SERDA), has been designed in order to reduce torsional rotor vibrations. Under shear mode, the ER absorber can exhibit various torsional damping and stiffness characteristics when an electric field is applied. A non-linear empirical model of the dynamic behavior of ER materials has been developed. An On-Off control strategy has been applied and absorber efficiency measured. The results show that the ER dynamic absorber exhibits very good performances.

Keywords: Electrorheological fluids, Torsional vibration, ER dynamic absorber, Smart Materials

5.1 Introduction

Electrorheological (ER) fluids are attractive materials that undergo very fast reversible changes in their rheological properties upon the application of electric fields (Winslow, 1949). These fluids can potentially be applied in many industrial areas (Block and Kelly, 1988); they may be used to control vibrations (Stanway et al, 1996) and structural damping or rotor squeeze film dampers , especially for active suspensions (Choi and Kim, 2000) or seismic control (Symans and Constantinou, 1999), through the application of high electric fields in real time. Certain industrial products have indeed been developed using ER fluids, such as vibration insulators, clutches, brakes, shock absorbers, etc.

Torsional rotor vibrations are undesirable phenomena which are very difficult to control in rotating systems. Many methods can be used to reduce such vibrations, and a common method involves the use of dynamic absorbers (Den Hartog, 2008); however, because the physical parameters of dynamic absorbers are constant, their frequency range of efficiency is tight, and thus not really suitable for systems with variable speeds. To remedy this, a damping could be added to the absorber, but this would lead to a loss of efficiency at the main frequency. Thus, given their variable properties, smart materials may be used to increase the frequency range in order to control vibration.

Previous studies have allowed the development of a new very efficient electrorheological fluid (Sun et al, 2004). In shear mode, the ER absorber can exhibit various damping and stiffness characteristics when an electric field is applied. In this study, the dynamical behavior of ER fluids in shear mode is experimentally observed and a mathematical model of the shear stress is developed from empirical analysis. This rheological model allows the exploration of the suitability of ER fluids to control the torsional vibrations of rotors through simulations. A new ER dynamic absorber working in torsion, and called the Smart ER Dynamic Absorber (SERDA), is thus proposed to control the torsional vibrations of a rotor system. Theoretical analyses and simulations of the smart ER dynamic absorber are introduced in order to understand the effects of the electric field on torsional damping and

stiffness. A non-linear empirical model is developed to describe the dynamic efficiency of the ER fluid which will be used in the smart ER dynamic absorber. The measurements of the absorber efficiency have been carried out based on an On-Off control strategy.

5.2 Modeling of the ER fluids in shear mode

5.2.1 Steady-state modeling of the ER fluids in shear mode (Quasi-Bingham model)

Generally, most ER fluids exhibit Bingham rheological behaviors and shear-thinning properties. However, while the Bingham model is good enough for describing the ER behavior at high shear speeds, it is nevertheless an approximated model, and obviously, the shear-thinning effect cannot be exactly described by this linear relation. To explain the complex phenomenon, a new model called the Quasi-Bingham model is developed in this study, and can explain the rheological behavior of ER fluids very well. Quasi-Bingham equations can be written in detail as follows:

$$\begin{aligned}
 \tau &= \tau_{yQB} + \eta_{\infty} \dot{\gamma} \quad \text{or} \quad \tau = \eta_{\infty} \dot{\gamma} && \text{when} \quad E = 0 \\
 \tau &= \tau_{yQB} + \eta_0 \dot{\gamma} && \text{when} \quad E \neq 0, \quad \dot{\gamma} \leq \dot{\gamma}_1 \\
 \tau &= \tau_{yQB} + \eta_{\infty} \dot{\gamma} + (\eta_0 - \eta_{\infty}) \frac{\dot{\gamma}}{1 + (t\dot{\gamma})^n} && \text{when} \quad E \neq 0, \\
 \tau &= \tau_{yQB} + \eta_{\infty} \dot{\gamma} && \text{when} \quad E \neq 0, \quad \dot{\gamma} \geq \dot{\gamma}_2
 \end{aligned} \tag{5.1}$$

- τ is the shear stress (Pa);
- E is the electric field (V/mm);
- τ_{yQB} is the elastic yield stress (Pa) which is dependent on the strain and on the applied electric field E ; according to the dielectric loss model by Hao et al (2000), the yield stress τ_{yQB} is a function of E^2 ;
- $\dot{\gamma}$ is the shear rate (1/s) : $\dot{\gamma} = \frac{d\gamma}{dt}$; γ is the strain;

- η_0 is the zero shear viscosity. It is defined as the value at a very low shear rate, and is a function of E;
- η_∞ is the infinite shear viscosity. It is defined as the value at very high shear rates;
- The parameter “n” is known as the Cross Rate Constant (Cross, 1965); it is a dimensionless factor and is a measurement of the degree of dependence of viscosity on the shear rate in the shear-thinning region;
- “t” is known as the Cross Time variable and has a dimension of time; the reciprocal, $1/t$, gives a critical shear rate that is a useful indicator of the onset shear rate for shear thinning;
- $\dot{\gamma}_1, \dot{\gamma}_2$ are two critical shear rates; the values can be obtained by using the two equations:

$$\begin{aligned} 1 + (t\dot{\gamma}_1)^n &\approx 1 \\ \dot{\gamma}_2 &\gg 1/t \end{aligned} \tag{5.2}$$

5.2.2 Rheological Behaviors of ER fluids

To study the effect of ER fluids on the dynamic absorber, a home made ER suspension composed of diatomite, called ETSEF40-20, is used. The terms 40 and 20 indicate the averaged size (μm) of particles and the mass concentration of fluid, respectively. The rheological properties of this ER fluid are measured with a Couette viscosimeter (Sun et al, 2009) under DC electric fields varying from 0 to 3500 V/mm (Figure 5.1), which allows the for measurement of the torque induced by the ER fluid and the computing of the shear stresses with the shear rates.

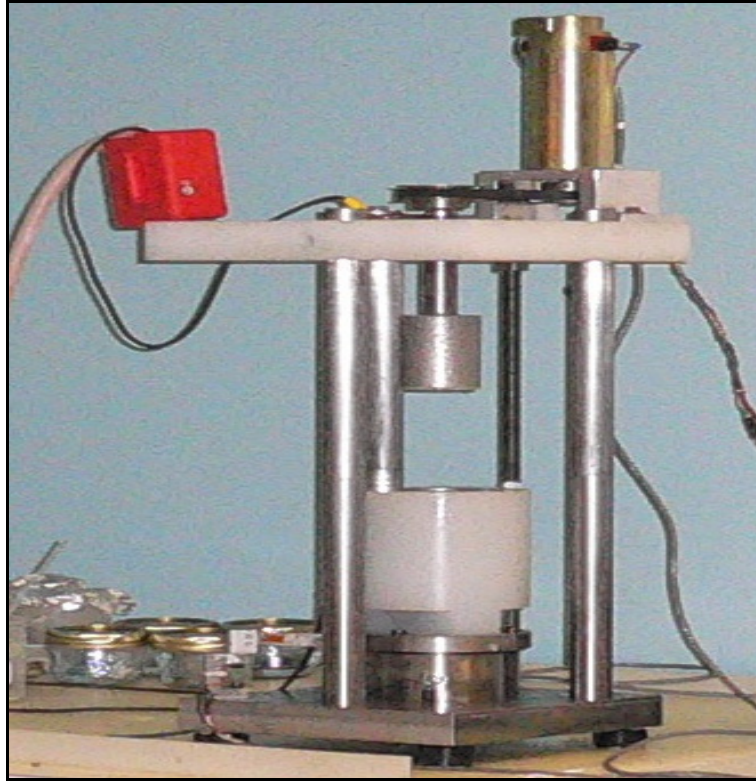


Figure 5.1 Couette viscosimeter.

Based on these measurements, the parameters (τ_{yQB} , η_0 , η_∞ , t and n) of the equation (5.1) can be estimated according the electric field strength. The Least Square method was used to conduct the regression analysis in order to determine these parameters. In Table 5.1, we give the fitting values for the ETSERF40-20, as well as the coefficient of determination R^2 and *adjusted* R^2 , obtained under different electric field strengths. As R^2 and *adjusted* R^2 are closed, the results may be considered as reliable.

Table 5.1 Fitting values of τ_{yQB} , η_0 , η_∞ , t and n

E(V/mm)	n	t	τ_{yQB}	η_∞	$\eta_0 - \eta_\infty$	η_0	R^2	$R^2_{adj.}$
0	1	0.0116	0	0.1993	0	0.1993	0.973	0.970
250	1	0.0214	3.4237	0.1845	0.0071	0.2064	0.995	0.995
500	1	0.735	2.3137	0.1752	8.7946	8.9939	0.995	0.994
750	1	0.7	4.5927	0.1595	19.9601	20.1594	0.989	0.988
1000	1	0.664	12.6967	0.1737	27.244	27.4433	0.983	0.982
1250	1	0.59	28.0251	0.1896	31.6035	31.8028	0.978	0.975
1500	1	0.604	51.5531	0.213	38.8105	39.0098	0.972	0.969
1750	1	0.572	66.4128	0.2406	53.7906	53.9899	0.973	0.969
2000	1	0.545	102.7807	0.2714	57.8874	58.0867	0.963	0.958
2250	1	0.505	125.2692	0.268	72.3545	72.5538	0.957	0.951
2500	1	0.484	171.1729	0.2593	80.3222	80.5215	0.978	0.975
2750	1	0.433	197.7744	0.2589	86.7181	86.9174	0.966	0.961
3000	1	0.43	250.4308	0.2271	93.2866	93.4859	0.983	0.981
3250	1	0.425	298.0804	0.1872	102.1746	102.3739	0.979	0.976
3500	1	0.424	342.1745	0.2668	104.4536	104.6529	0.972	0.967
Average	1		$27.04 \times 10^{-9} E^2$	0.218	$29.4 \times 10^{-3} E$			

The predicted and measured rheograms of ETSERF40-20 are shown in Figure 5.2 under different electric fields. It can be seen that the regression results are very comparable with the experimental results.

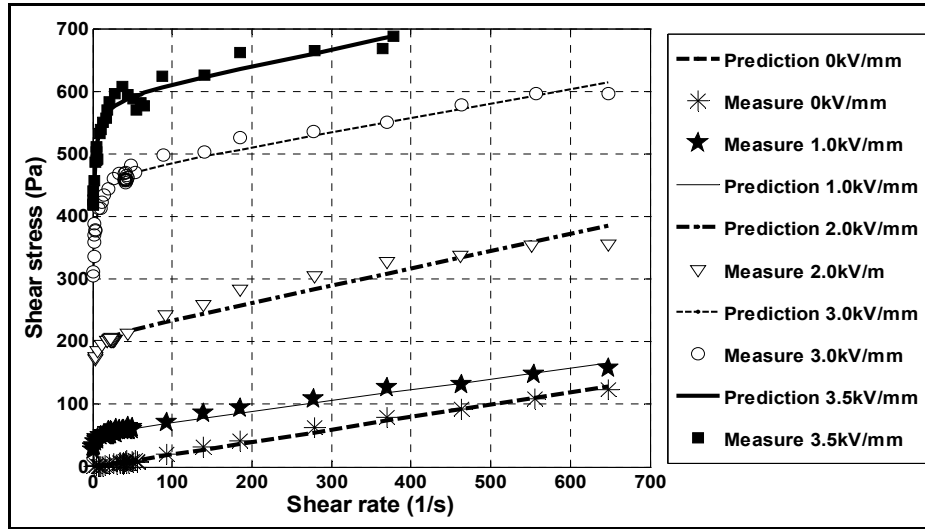


Figure 5.2 Predicted rheograms of the ETSERF40-20 fluid under various electric fields.

An empirical equation (Equation 5.3) for the stresses has been developed for ETSERF40-20 from table 5.1, based on the three assumptions, where the Cross time parameter “ t ” is function of electrical field, and depends on the visco-elasticity of material. From table 5.1, we can see that the parameter t decreases when the electrical field strength increases. As seen in equation (5.2), the decrease of “ t ” parameter with the electric field implies an increase in the shear rate range in the η_0 viscosity region.

This equation is very useful for the design of the dynamic absorber and vibration control. However, for very low values of electric field ($E=0$ and 250 V/mm), “ t ” is not reliable since the fluid presents nearly a Newtonian behavior.

$$\tau = \tau_{yQB} + \eta_{\infty} \dot{\gamma} + \frac{\dot{\gamma}}{1 + (t\dot{\gamma})^n} \quad (5.3)$$

$$\tau = 27.04 \times 10^{-9} E^2 + 0.218 \dot{\gamma} + 29.4 \times 10^{-3} E \frac{\dot{\gamma}}{1 + t\dot{\gamma}}$$

Equation (5.3) allows to identification of the following relationships:

$$\begin{aligned} \tau_{yQB} &= 27.04 \times 10^{-9} E^2 \\ \eta_{\infty} &= 0.218 \\ \eta_0 &= 29.4 \times 10^{-3} E + 0.218 \\ n &= 1 \end{aligned} \quad (5.4)$$

The theoretical yield stresses and the zero shear viscosity are plotted in Figures 5.3 and 5.4, respectively, and compared with the experimental results; the predicted and measured results are very similar.

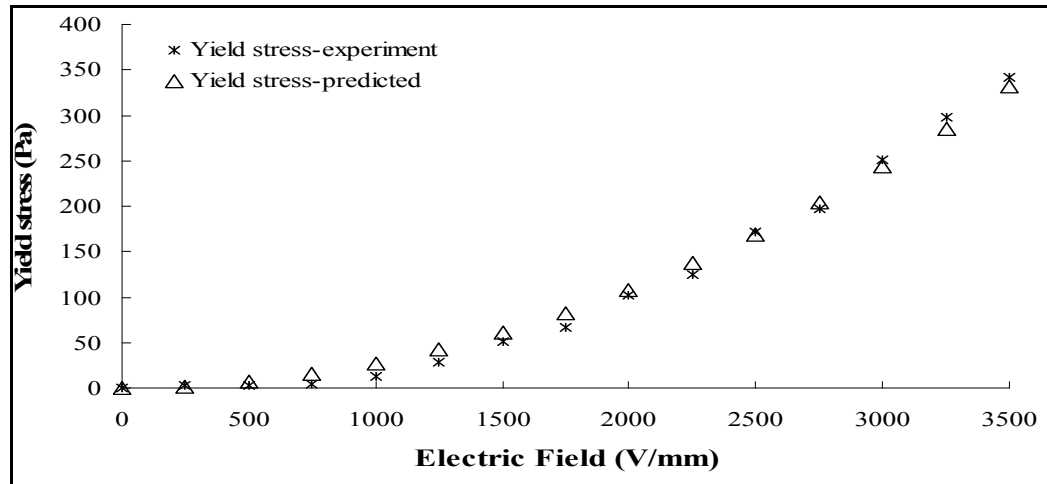


Figure 5.3 Experimental and predicted Yield stresses with electric fields.

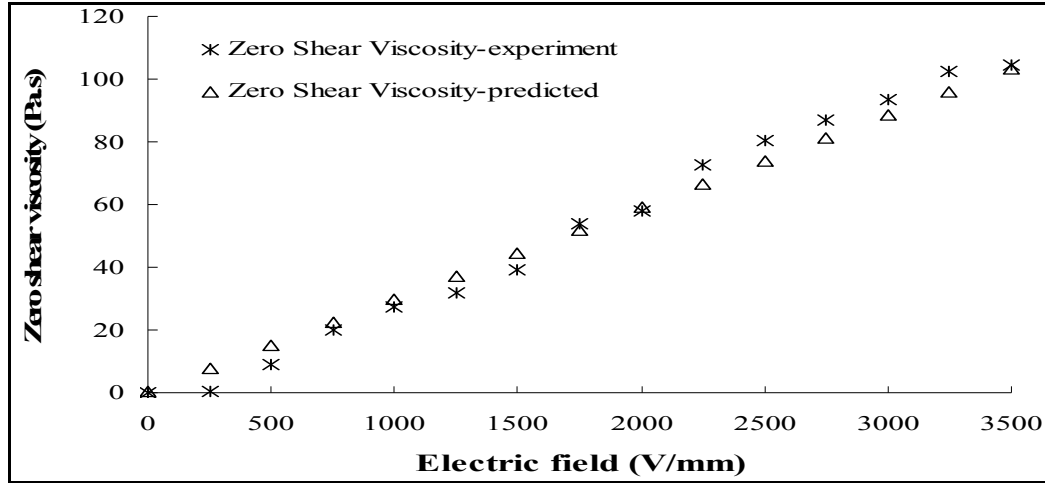


Figure 5.4 Experimental and predicted zero shear viscosity with electric field.

5.2.3 Oscillatory dynamic model in shear mode (General Quasi-Bingham model in shear mode)

The previous model (Equation 5.1) is based on steady-state shear assumption (Sun et al, 2006). It describes the rheological behaviors of ER fluids when the yield stress has been exceeded, but it cannot accurately describe the fluid behavior when the ER fluid is subjected to very small strain below the yield point. Consequently, it is hard to give an exact explanation of the oscillatory dynamic phenomena of ER fluids using this model directly. Many experimental results show that ER fluids exhibit a visco-elastic behavior under an electric field. Providing an exact description of the material characteristics in the pre-yield region is crucial in dynamic applications such as dampers, where the entire hysteresis cycle needs to be predicted. Therefore, some modifications need to be brought to the Quasi-Bingham model in describing the rheological behavior when the ER fluid is subjected to oscillations.

5.2.3.1 Introducing visco-elasticity in the pre-yield region

The shear stress must exceed the yield stress value for the material to be activated. Many authors have used this characteristic to describe the observed boundary values for their

experiments, and this is very useful when the ER material is subjected to a uni-directional shear. However, when the fluid is submitted to vibrations, the equations (5.1) do not take into account the fluid elasticity, and can thus not describe the material behavior at values below the yield stress when the ER fluid is excited by dynamic oscillations. In order to compensate this shortcoming, the following extension of the Quasi-Bingham model is proposed by modifying the constitutive model proposed by Lee and Cheng (2000):

$$\begin{aligned}
 \tau &= G_0 \gamma \left(1 - e^{-(\gamma_y/|\gamma|)}\right) + \eta_\infty \dot{\gamma} & \text{when } E &= 0 \\
 \tau &= G_0 \gamma \left(1 - e^{-(\gamma_y/|\gamma|)}\right) + \eta_0 \dot{\gamma} & \text{when } E \neq 0, \quad \dot{\gamma} \leq \dot{\gamma}_1 \\
 \tau &= G_0 \gamma \left(1 - e^{-(\gamma_y/|\gamma|)}\right) + \eta_\infty \dot{\gamma} + (\eta_0 - \eta_\infty) \frac{\dot{\gamma}}{1 + (t|\dot{\gamma}|)^n} & \text{when } E \neq 0, \\
 \tau &= G_0 \gamma \left(1 - e^{-(\gamma_y/|\gamma|)}\right) + \eta_\infty \dot{\gamma} & \text{when } E \neq 0, \quad \dot{\gamma} \geq \dot{\gamma}_2
 \end{aligned} \tag{5.5}$$

where G_0 denotes the material modulus when the material works at small shear rates below the yield point and γ_y is the yield strain.

The modification of the Quasi-Bingham model can thus allow the description of the elastic behavior of the ER fluid under oscillation states. The yield stress is defined as the stress which causes shear deformation at infinitesimal shear rate, hence:

$$\tau_{yQB} = \lim_{\substack{\dot{\gamma} \rightarrow \infty \\ \dot{\gamma} \rightarrow 0}} \tau = G_0 \gamma_y \tag{5.6}$$

As expected for visco-elastic materials (Malkin, 1994), equation (5.5) presents two parts, the elastic yield stress $G_0 \gamma \left(1 - e^{-(\gamma_y/|\gamma|)}\right)$ and the viscous dissipation, which depends on shear rate.

In order to describe the visco-elasticity of ER fluids, the shear stress τ and strain γ are introduced in a complex form:

$$\tau = [G_1(\dot{\theta}) + iG_2(\dot{\theta})] \gamma = G_1(\dot{\theta}) \gamma + iG_2(\dot{\theta}) \gamma = \tau_1 + i\tau_2 \tag{5.7}$$

where G_1 , G_2 respectively denote the real and imaginary parts of material modules and $\dot{\theta}$ is the angular velocity.

If the ER material is subjected to a complex periodic strain:

$$\gamma = \gamma_0 e^{i\dot{\theta}t} \quad (5.8)$$

then we have the shear rate as follows:

$$\dot{\gamma} = \gamma_0 i\dot{\theta} e^{i\dot{\theta}t} = i\dot{\theta}\gamma \quad (5.9)$$

Based on equation (5.5) and taking into consideration equations (5.7), (5.8) and (5.9), we thus obtain the following equations:

$$\begin{aligned} \tau &= [G_1(\dot{\theta}) + iG_2(\dot{\theta})]\gamma = G_1(\dot{\theta})\gamma + iG_2(\dot{\theta})\gamma \\ \tau &= G_0 \left(1 - e^{-(\gamma_y/|\dot{\gamma}|)}\right) \gamma + \eta_\infty \dot{\gamma} + (\eta_0 - \eta_\infty) \frac{\dot{\gamma}}{1 + (t|\dot{\gamma}|)^n} \\ \tau &= G_0 \left(1 - e^{-(\gamma_y/|\dot{\gamma}|)}\right) \gamma + \eta_\infty i\dot{\theta}\gamma + (\eta_0 - \eta_\infty) \frac{i\dot{\theta}\gamma}{1 + (t|\dot{\gamma}|)^n} \\ \tau &= G_0 \left(1 - e^{-(\gamma_y/|\dot{\gamma}|)}\right) \gamma + i \left[\eta_\infty \dot{\theta} + (\eta_0 - \eta_\infty) \frac{\dot{\theta}}{1 + (t|\dot{\gamma}|)^n} \right] \gamma \end{aligned} \quad (5.10)$$

Equation 5.10 shows a non-linear relationship between stress and strain. The complex modulus can then be written as follows:

$$\begin{aligned} G_1 &= G_0 \left(1 - e^{-(\gamma_y/|\dot{\gamma}|)}\right) \\ G_2 &= \eta_\infty \dot{\theta} + (\eta_0 - \eta_\infty) \frac{\dot{\theta}}{1 + (t|\dot{\gamma}|)^n} \end{aligned} \quad (5.11)$$

The loss factor δ for ER material can be obtained as follows:

$$\delta = \frac{G_2}{G_1} \quad (5.12)$$

G_1 and G_2 are a function of the strain, the shear rate and the excitation frequency. G_1 represents the storage of elastic energy and G_2 represents the dissipative loss, and is non-linear.

5.2.3.2 Torsional damping and stiffness of ER Dynamic absorber

5.2.3.2.1 The ER dynamic absorber model

The vibration of a mechanical system may be described as a single degree of freedom (S.D.O.F), composed of the rotational inertia J_1 , torsional stiffness K_1 , and torsional damping C_1 . If the torsional vibration of the system is high, it can be assumed that its damping is negligible ($C_1=0$) and that the system is vibrating close to its natural frequency. The vibration control method in this system consists in adding another S.D.O.F. system, which is the dynamic absorber. The smart ER dynamic absorber is composed of a rotational inertia J_2 driven by the ER fluid, which can thus be modeled by a non-linear torsional spring (K_2), a linear viscous dashpot (C) and a non-linear viscous dashpot (C_{ER}). The resulting mechanical system is a two degrees of freedom system which is illustrated in Figure 5.5.

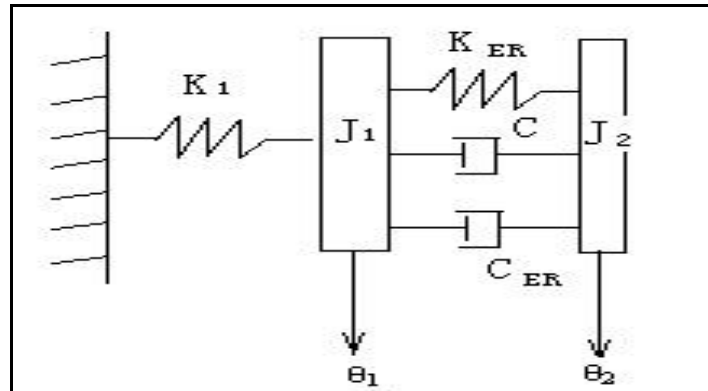


Figure 5.5 The ER torsional dynamic absorber.

The linear viscous dashpot C represents the viscous damping when the electric field is not applied, and the non-linear viscous dashpot C_{ER} represents the non-linear damping part which is introduced by the applying an electric field.

5.2.3.2.2 Measurement of torsional damping and stiffness of ER fluids

In order to characterize the torsional stiffness and damping of ER fluids, a rotational system has been designed (Figure 5.6). The two cylinders J_1 and J_2 serve as electrodes for the ER effect. R represents the internal radius of the outer cylinder, R_0 is the external radius of the inner cylinder, H is the height of the inner cylinder and e ($e = R - R_0$) is the oil film thickness. If the inner cylinder is fixed, the experimental mechanisms can be modeled as a S.D.O.F. torsional system in order to compute the equivalent damping and stiffness based on equations (5.5) of the General Quasi-Bingham model. Because the oil film e is very thin (1.4 mm), all estimations can be achieved by calculating the torque of the outer cylinder resulting from the effect of ER fluids by considering that the internal radius R of the outer cylinder is much greater than the oil film e ($R \gg e$).

When the electric field is not applied, the damping C of ER fluids can be calculated from equation (5.13). This damping is inherent, and it is not influenced by the electric field.

$$C = \frac{2\pi R^3 H \eta_{\infty}}{R - R_0}; \quad E = 0 \quad (5.13)$$

The torque M_{ER} which is due to the effect of the ER fluids, is composed of a non-linear torsional stiffness torque and a non-linear viscous torque, which depend on the electric field. It can be written as follows:

$$M_F = K_{ER} \theta + (C + C_{ER}) \dot{\theta} = K_{ER} \theta + C \dot{\theta} + C_{ER} \dot{\theta} = C \dot{\theta} + M_{ER} \quad (5.14)$$

$$\text{with } M_{ER} = K_{ER} \theta + C_{ER} \dot{\theta} \quad (5.15)$$

where K_{ER} is the non-linear torsional stiffness and, C_{ER} is the torsional non-linear damping coefficient.

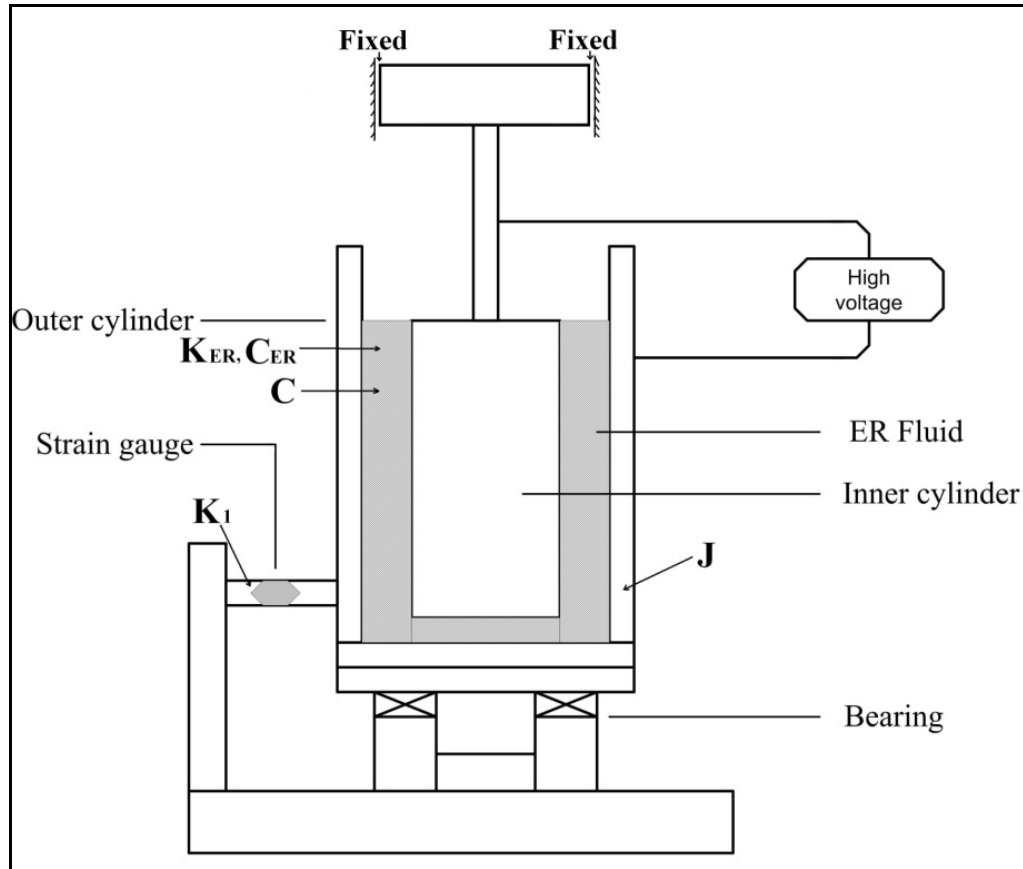


Figure 5.6 Experimental set-up for dynamic characteristics of ER fluids.

With the assumption ($R \gg e$), the torque can be expressed from Equation (5.14) as:

$$M_F = 2\pi R^2 H \tau = K_{ER} \theta + C \dot{\theta} + C_{ER} \dot{\theta} \quad (5.16)$$

By introducing equation (5.5), we obtain:

$$2\pi R^2 H \tau = (2\pi R^2 H) \left(G_0 \gamma \left(1 - e^{-\left(\frac{\gamma_y}{|\gamma|} \right)} \right) + \eta_\infty \dot{\gamma} + (\eta_0 - \eta_\infty) \frac{\dot{\gamma}}{1 + (t|\dot{\gamma}|)^n} \right) \quad (5.17)$$

Since the two cylinders are closed, the thickness is therefore thin ($R \gg e$), and the shear rate $\dot{\gamma}$ may be simplified as follows:

$$\dot{\gamma} = \frac{V}{h} \cong \frac{R}{e} \dot{\theta} \quad (5.18)$$

By substituting equation (5.18) into the equation (5.17), we obtain:

$$\begin{aligned} 2\pi R^2 H \tau &= 2\pi R^2 H G_0 \gamma \left(1 - e^{-\left(\frac{\gamma_y}{|\gamma|} \right)} \right) + 2\pi R^2 H \eta_\infty \frac{R \dot{\theta}}{e} + 2\pi R^2 H (\eta_0 - \eta_\infty) \frac{1}{1 + \left(t \left| \frac{R \dot{\theta}}{e} \right| \right)^n} \left(\frac{R \dot{\theta}}{e} \right) \\ &= 2\pi R^2 H G_0 \left(1 - e^{-\left(\frac{\gamma_y}{|\gamma|} \right)} \right) \gamma + \frac{2\pi R^3 H \eta_\infty}{e} \dot{\theta} + \frac{2\pi R^3 H (\eta_0 - \eta_\infty)}{e \left[1 + \left(t \left| \frac{R \dot{\theta}}{e} \right| \right)^n \right]} \dot{\theta} \\ &\quad \Downarrow \quad \quad \quad \Downarrow \quad \quad \quad \Downarrow \\ &= K_{ER} \theta \quad \quad \quad + C \dot{\theta} \quad \quad \quad + C_{ER} \dot{\theta} \end{aligned} \quad (5.19)$$

Then, by analogy to Equation (5.13), we can obtain the damping and stiffness parameters of ER fluids:

$$C_{ER} = \frac{2\pi R^3 H (\eta_0 - \eta_\infty)}{(R - R_0) \left[1 + \left(t R \left| \dot{\theta} \right| / (R - R_0) \right)^n \right]} = C'_{ER} \frac{1}{1 + \left(t R \left| \dot{\theta} \right| / (R - R_0) \right)^n} \quad (5.20)$$

where

$$C'_{ER} = \frac{2\pi R^3 H(\eta_0 - \eta_\infty)}{(R - R_0)} \quad (5.21)$$

K_{ER} is a non-linear complex stiffness, and it can be expressed as:

$$K_{ER} = K_{ER0} \left(1 - e^{-\left(\frac{\gamma_y}{\gamma}\right)} \right) \quad (5.22)$$

By substituting equation (5.6) and $\gamma = \frac{R}{e}\theta$ into equation (5.19) and (5.22), the maximum value K_{ER0} can be calculated directly as follows:

$$K_{ER0} = \frac{2\pi R^2 H G_0 \gamma}{\theta} = \frac{2\pi R^3 H G_0}{e} = \frac{2\pi R^3 H \tau_{yQB}}{e \gamma_y} \quad (5.23)$$

5.3 Smart ER Dynamic Absorber (SERDA)

The ER dynamic absorber that we have designed in rotational shear mode is described in Figures 5.5 and 5.6. Viscous damping and stiffness can be controlled by varying the electric field. This method allows us to establish a semi-active control of torsional vibration for rotating systems. The inertia, J_2 is free to rotate and spins through an angle θ_2 due to the shearing effect of the ER fluids providing a torque M_{ER} .

If an external harmonic torque $M = M_0 \cos \omega t$ is applied, the equations of motion become:

$$\begin{aligned} J_1 \ddot{\theta}_1 + K_1 \theta_1 + (C + C_{ER})(\dot{\theta}_1 - \dot{\theta}_2) + K_{ER}(\theta_1 - \theta_2) &= M \\ J_2 \ddot{\theta}_2 + (C + C_{ER})(\dot{\theta}_2 - \dot{\theta}_1) + K_{ER}(\theta_2 - \theta_1) &= 0 \end{aligned} \quad (5.24)$$

The uncoupled undamped natural frequencies of the primary system (ω_{11}) and of the absorber (ω_{22}) can respectively be written as:

$$\omega_{11} = \sqrt{\frac{K_1}{J_1}} \text{ and } \omega_{22} = \sqrt{\frac{K_{EReq}}{J_2}} \quad (5.25)$$

Hence, the amplitude of vibration of the primary inertia J_1 can be expressed as:

$$\frac{\theta K_1}{M_0} = \sqrt{\frac{(2\zeta\gamma)^2 + (\gamma^2 - \beta^2)^2}{(2\zeta\gamma)^2(\gamma^2 - 1 + \mu\gamma^2)^2 + [\mu\gamma^2\beta^2 - (\gamma^2 - 1)(\gamma^2 - \beta^2)]^2}} \quad (5.26)$$

with:

$$\mu = \frac{J_2}{J_1}; \gamma = \frac{\omega}{\omega_{11}}; \beta = \frac{\omega_{22}}{\omega_{11}}; \zeta = \frac{C + C_{eq}}{2J_2\omega_{11}} \quad (5.27)$$

An optimum value can theoretically be found (Den Hartog, 2008) for the design of a damped dynamic absorber accordingly with the inertia ratio μ :

$$\beta_{opt} = \left(\frac{1}{1 + \mu} \right) \quad (5.28)$$

$$\zeta_{opt} = \sqrt{\frac{3\mu}{8(1 + \mu)}}$$

If we consider an inertia ratio μ of 0.25 as is usually applied, we obtain the optimum values $\beta_{opt} = 0.8$ and $\zeta_{opt} = 0.27$. Figure 5.7 shows the influences of the parameters β on the amplitude of vibration of the primary inertia for different damping ratios ζ .

However, the damping and stiffness of ER fluids are coupled and change at the same time as a function of the electric field, thus making it impossible to independently control the optimal damping and stiffness values.

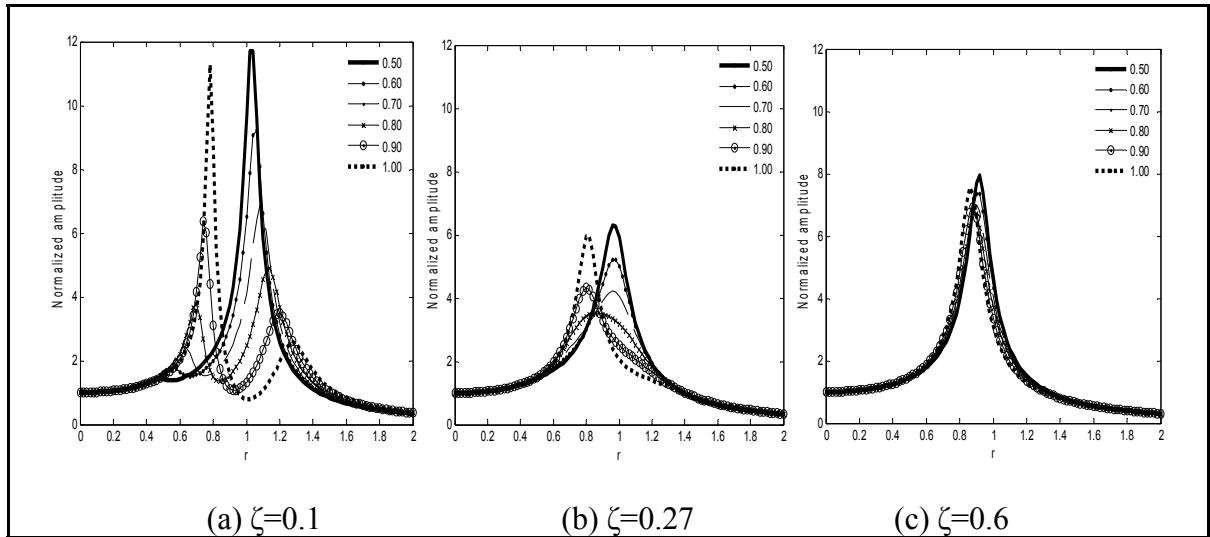


Figure 5.7 Normalized amplitude of the primary inertia.

5.4 Simulation and experimental results

5.4.1 Simulation of yield stress, strain and shear modulus

Based on the measurements carried out with ETSERF40-20, the yield strain γ_y and the shear modulus G_0 can be estimated by using the equations (5.6), (5.22) and (5.23) under different electrical fields. Figure 5.8 shows the elastic yield stresses under different electric fields. From these curves, it can be seen that the yield stress-strain relationship is non-linear. The higher the electric field, the higher the yield stresses obtained.

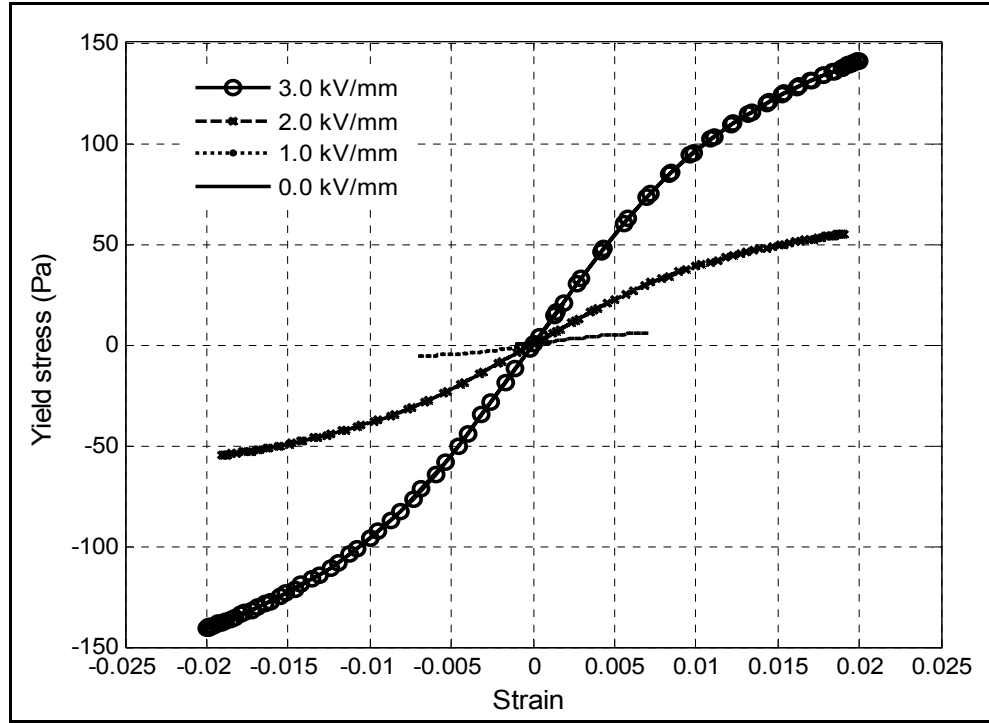


Figure 5.8 Non-linear yield stress-strain under different electric fields.

The curves for γ_y and G_0 are described in Figures 5.9 and 5.10, respectively, with their regression curves. The yield strain and shear modulus increase with the electric field, but the yield strain presents an asymptotic behavior at high electric fields.

The hysteresis loop of viscoelastic materials can be obtained in the stress-strain diagram by simulations of the aforementioned General Quasi-Bingham model. By substituting $\dot{\gamma}$ and $\gamma = \gamma_y \cos 2\pi fT$ into equation (5.5), the hysteresis loop can be plotted. Figure 5.11 illustrates the hysteresis loop of ER fluids under different electric fields by considering the fitting values (see Table 5.1) of all of parameters for the ETSERF40-20 fluid. We can see that the damping, defined by the area under the curves, increases with the electric field.

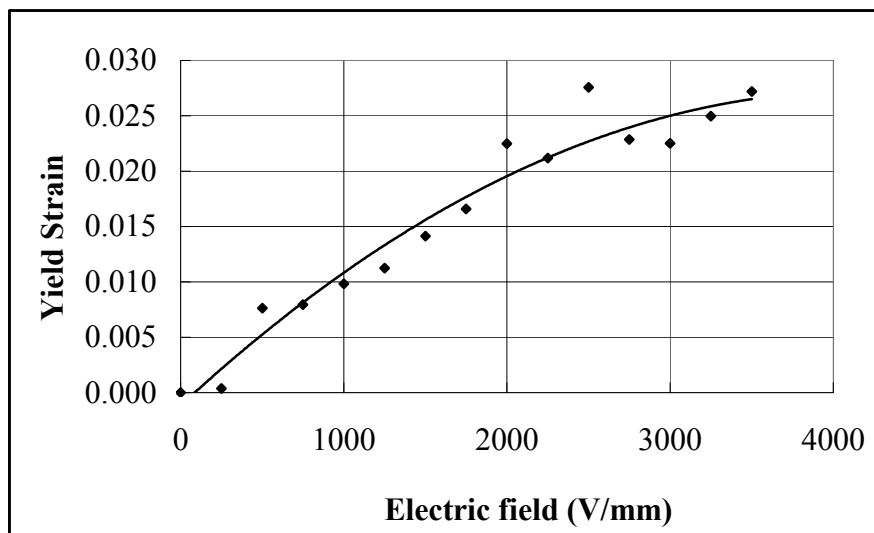


Figure 5.9 Yield strain vs electric field.

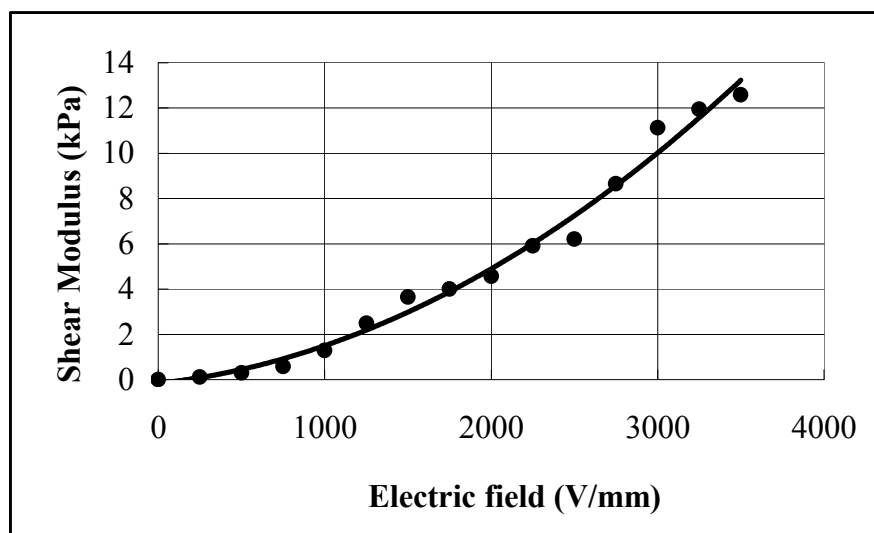


Figure 5.10 Shear modulus vs electric field.

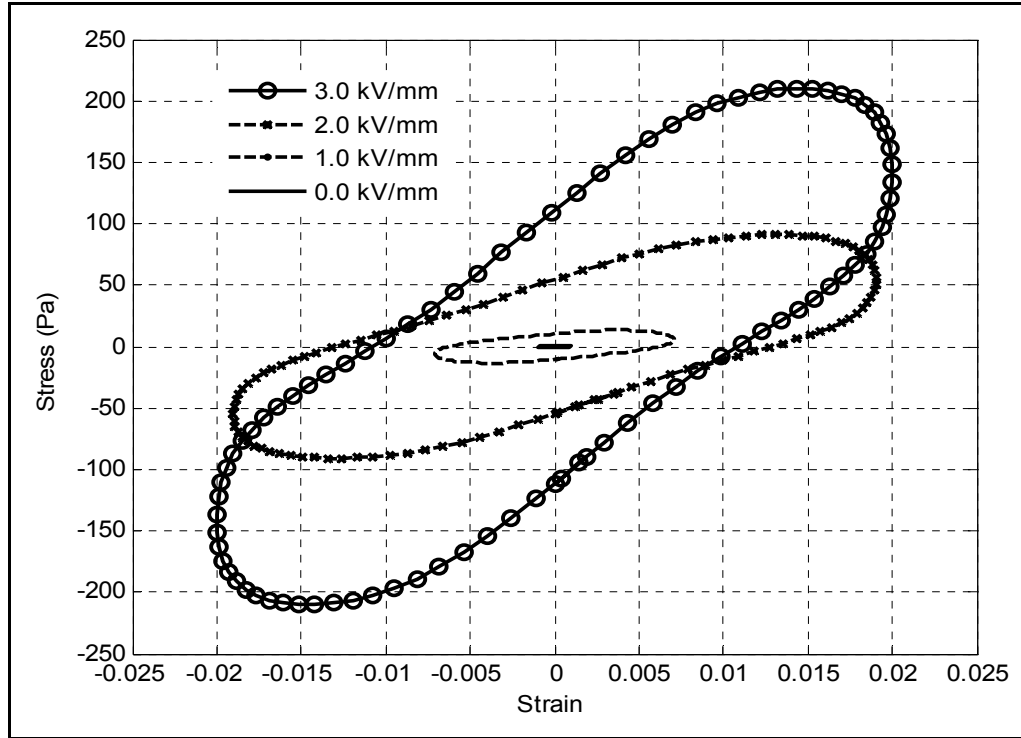


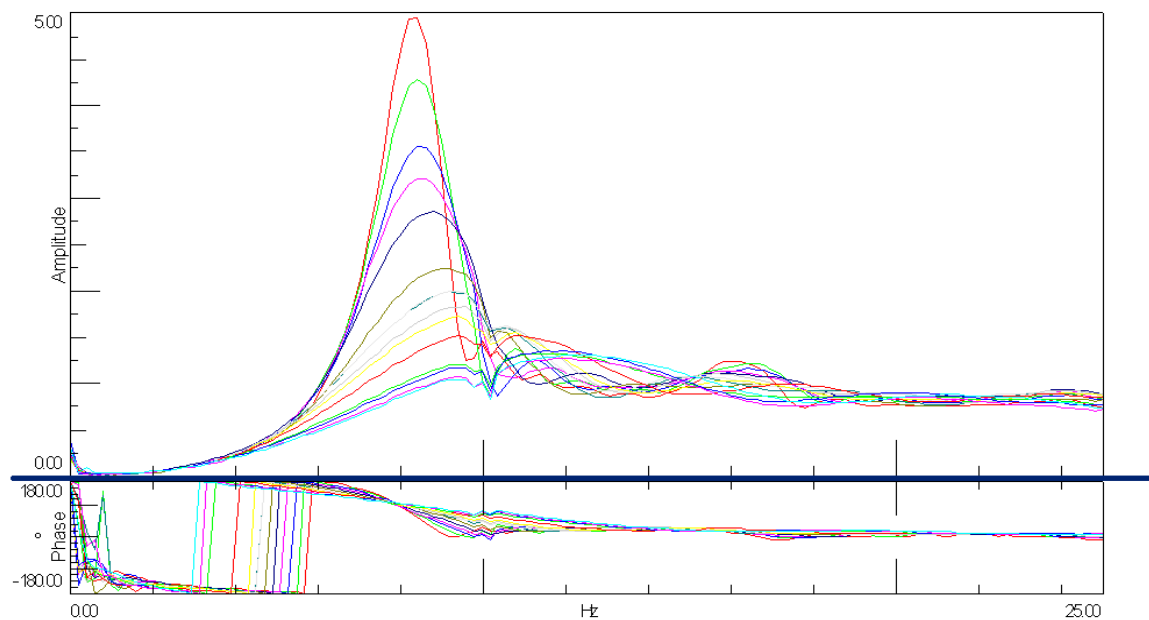
Figure 5.11 Hysteresis loops of ER fluids under different electric fields.

5.4.2 Experimental identification of ERF dynamic parameters in shear mode (S.D.O.F. system)

In order to identify the dynamic parameters of ER fluids, a device was designed as described in Figure 5.6. The investigated fluid is filled between two coaxial cylinders, and the inner cylinder has been fixed. An accelerometer is attached to the outer cylinder J_1 ($4.25 \times 10^{-3} \text{ kg.m}^2$), which is linked to the support using a flexible beam. This flexible beam may be modeled as a torsional spring measured to $K_1 = 11.03 \text{ N.m/rad}$, with no damping. The rotor system is excited by a torque M , and the differential equation of motion for an S.D.O.F. system in torsion is given as follows:

$$J\ddot{\theta} + (C + C_{eq})\dot{\theta} + (K_1 + K_{ER})\theta = M \quad (5.29)$$

The mechanical system was excited in torsion by an impact hammer and the torsional responses measured with an accelerometer in the tangential direction. The measurement of the transfer function between the responses and force allows the extraction the modal parameters under various electric fields. The Frequency Response Functions (FRF) of the primary system was measured for each electric field from 0 to 3500 V/mm (Figure 5.12). These curves allows the identification of natural frequencies (frequencies corresponding to a maximum of the imaginary part of the FRF) and of damping rates (computed from the 3 dB rule whose frequencies are extracted from the maximum and minimum of the real part of FRF). It can be seen that the assumption of a S.D.O.F. system is appropriate, since only one main frequency appears. Furthermore, it can be seen that the maximum amplitude of outer cylinder vibration decreases as the electric field strength increases, and that the resonance frequency increases as well. This means that the damping and torsional stiffness K_{ER} of the rotor system both increase simultaneously with the electric field. The stiffness was computed from the natural frequency identification, knowing the rotating inertia.



red line ($E=0\text{V/mm}$), green ($E=250\text{V/mm}$).....light blue ($E=3500\text{V/mm}$).

Figure 5.12 FRF of ER fluids with electric fields.

Figure 5.13 and 5.14 shows the evolution of torsional stiffness and damping ratio with the electric field, respectively. The torsional stiffness K_{ER} varies from 0.12 to 13.33 N.m/rad, and the damping ratio varies from 4.8% to 31.16% as the electric field is varied from 0 to 3500 V/mm.

Similar results were obtained from simulations. From the simulation results shown in Figure 5.11, the equivalent damping ratio was computed to 26% for a 2000 V/mm electric field, while the measurement gives 23% for the same excitation.

The continuous lines of Figures 5.13 and 5.14 represent the polynomial regressions. The torsional stiffness (N.m/rad) was found to increase following a 2nd order polynomial function with the electric field (kV/mm). On the other hand, the damping ratio (%) saturates at very high electric field strength with a 6th order polynomial function. The following equations have been extrapolated with a coefficient of determination R^2 of 0.986:

$$\begin{aligned} K_{ER} &= 0.9603E^2 + 0.6586E \\ \zeta &= 0.5053E^6 - 5.2716E^5 + 20.634E^3 + 36.873E^2 - 7.1523E + 5.187 \end{aligned} \quad R^2 = 0.986 \quad (5.30)$$

Therefore, the design of a dynamic absorber must consider these variations of damping and stiffness at the same time an electric field is applied.

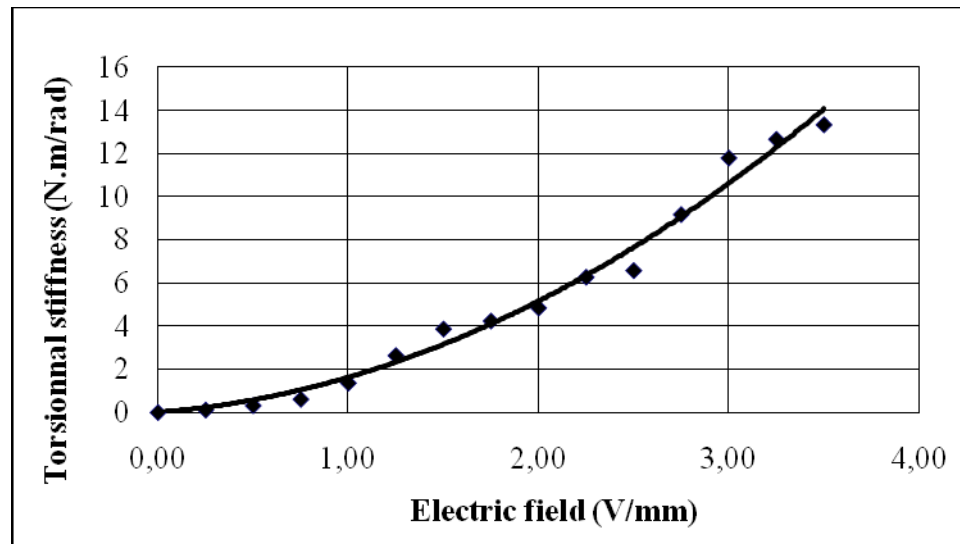


Figure 5.13 Variation of torsional stiffness with electric field.

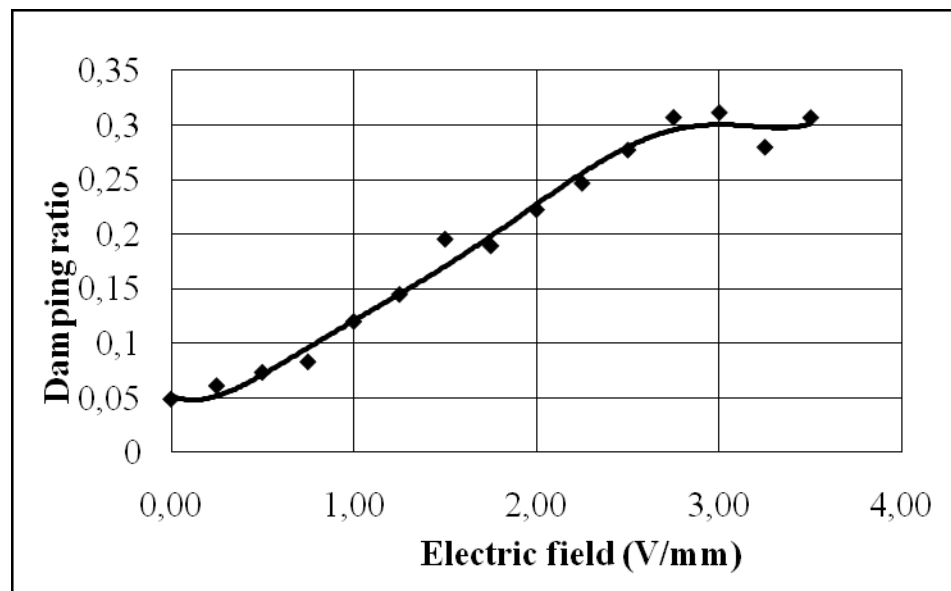


Figure 5.14 Variation of damping ratio with electric field.

5.4.3 Design of Smart ER Dynamic Absorber (SERDA)

For the design of the ER dynamic absorber, the inner inertia J_2 is unblocked and set free to spin as described in Figure 5.6. The outer cylinder works as a primary system with the torsional stiffness K_1 (11.03 N.m/rad) and an inertia J_1 (4.25×10^{-3} kg.m²). The inner cylinder (secondary system) acts as the absorber, and is modeled with an inertia of J_2 (1.06×10^{-3} kg.m²). Consequently, the value of inertia ratio μ was designed close to 0.25, and the ER fluid was filled between the two cylinders. The stiffness K_{ER} and damping C_{ER} are produced when the electric field is applied to the system, and their values will change as the electric field strength varies. The outer cylinder (primary system) was excited in torsion by an impact hammer in order to excite the entire frequency range, and its vibratory response was measured in the tangent direction under different electric fields. The FRF amplitudes of the primary system are illustrated in Figure 5.15. Along with the increase in the electric field, the secondary system creates two natural frequencies that vary with the ER stiffness. Similar results have been obtained by simulation by using equations (5.26) and (5.30), as shown in Figure 5.16.

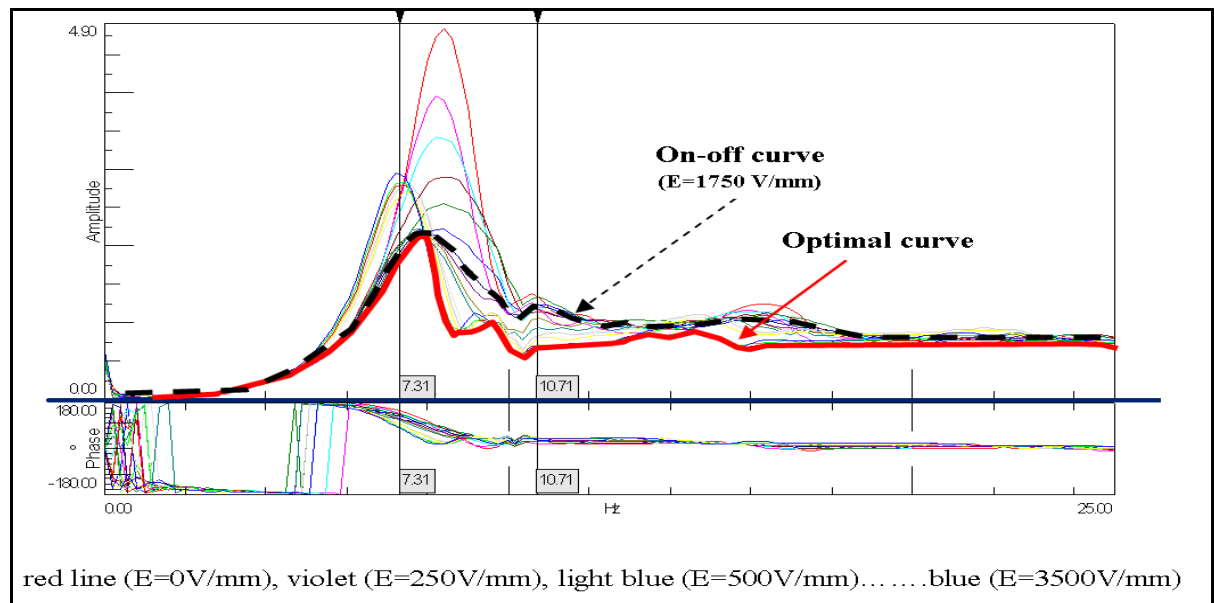


Figure 5.15 Efficiency of the absorber under different electric fields.

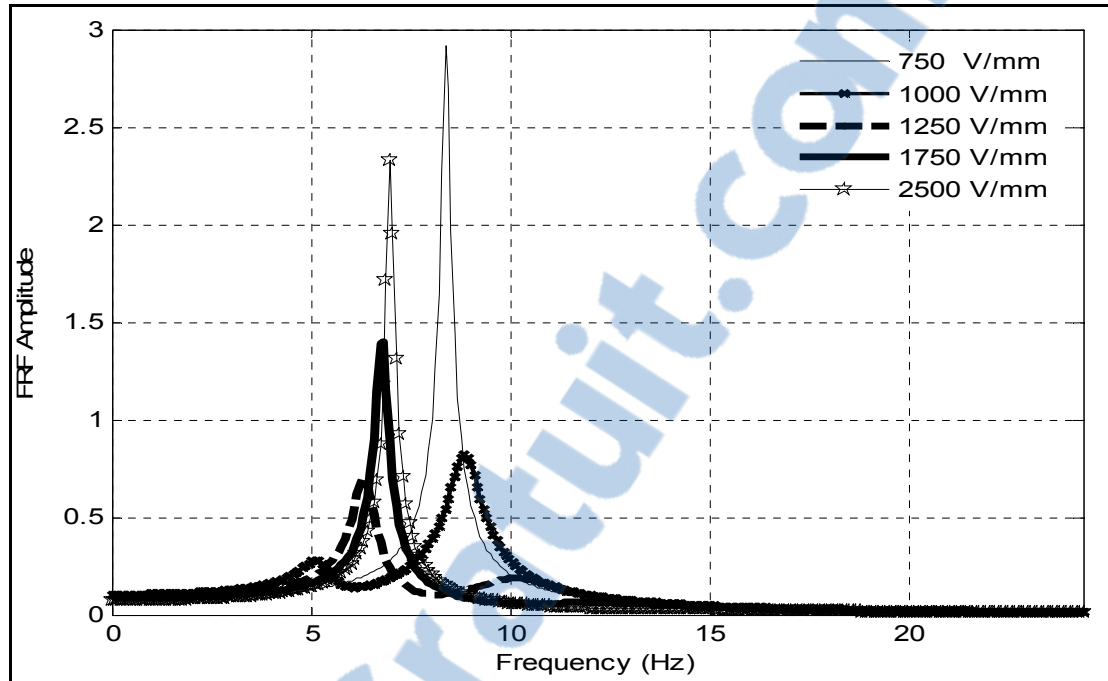


Figure 5.16 Simulation of the SERDA absorber under different electric fields.

5.4.4 Control strategies

As expected for a two D.O.F. system, two natural frequencies are observed accordingly with the variation of the electric field. While an ordinary dynamic absorber only works into a very narrow-band frequency range, it can be seen from Figure 5.15 that the frequency range of SERDA is enlarged when the electric field is applied, and that the FRF amplitudes of the primary system show minimum values under a large frequency range, thus allowing the operating speed range to be widened.

The maximum values of the FRF amplitudes of the primary system have been investigated and the results show that they decrease as the electric field increases. Optimal values are obtained as the electric field varies between 1250 V/mm and 2000 V/mm, which represents an improvement $(100 \times (\text{Max amplitude} - \text{Min amplitude}) / \text{Min amplitude})$ greater than 150 % in terms of controlling the vibrations. Because of the saturation of damping at very high electric fields (Figure 5.14), the improvement is attenuated somewhat when the electric field

varies between 2500V/mm and 3500V/mm. The experimental results are described in Figure 5.17 and are compared with the simulation results. Using equations (5.26) and (5.30), the maximum amplitudes of the primary system are computed at each electric field. It can be seen in Figure 5.17 that the results are comparable, with the greatest differences appearing at low electric fields ($E \leq 500V$), since the absorber works like a Houdaille damper (Inman, 1994), due to its low stiffness. Equation (5.26) is thus not valid beyond this point and should be modified.

In fact, the stiffness and damping of fluids are mutually dependent, and can therefore not be individually controlled by applying the electric field. Consequently, optimal damping and optimal stiffness cannot be achieved at the same time. In this paper, the control strategy applied is the ON-OFF strategy, as can be seen in Figure 5.15 (broken line), at an electric field of $E=1750V/mm$ for example. In a future work, an adaptative strategy will be developed, and the electric field will have to vary with the excitation frequency, as shown in the red bold line in Figure 5.15.

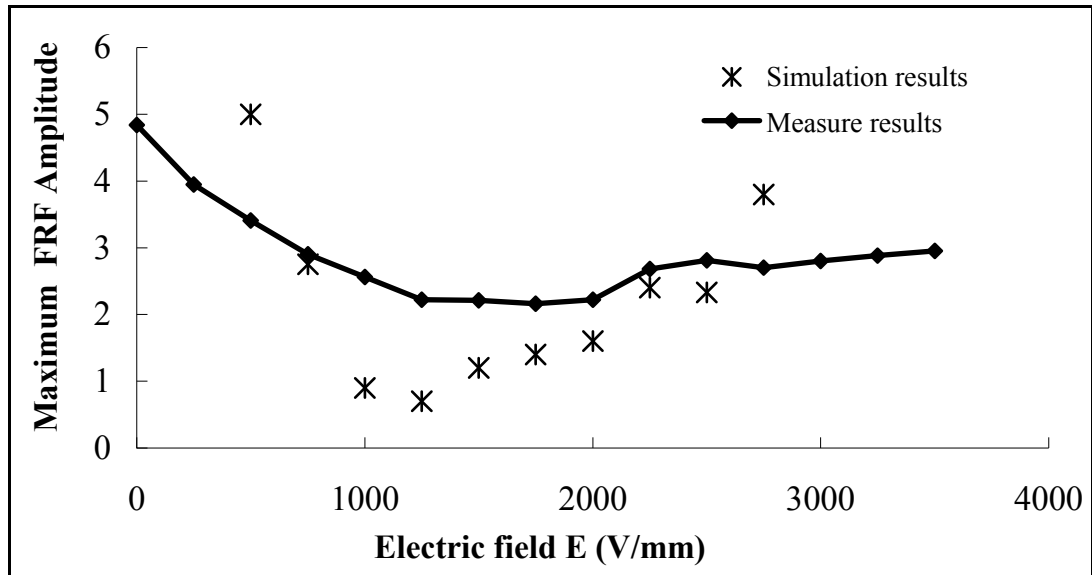


Figure 5.17 Maximum FRF amplitude of the primary system with electric fields.

5.5 Conclusions

The aim of this paper is to develop and characterize a new electrorheological dynamic torsional absorber, called the Smart Electrorheological Dynamic Absorber (SERDA) to be used in reducing torsional rotor vibrations. When ER materials are subjected to strong electric fields, they exhibit remarkable changes in material properties. A home made ER fluid, called ETSERF40-20, is developed. Visco-elastic behavior is the dominant characteristic of ER fluids at low strains, and a yielding mechanism dominates the ER behavior at high shear rates. When the shear rate increases, the behavior of ER fluids approaches what is seen in the Quasi-Bingham model and the applied shear stress must overtake a yielding level. However, this assumption is violated when an oscillating shear motion occurs. Therefore, a general constitutive Quasi-Bingham model is developed in order to describe the material behavior. The dynamic characteristics of the ER material under oscillating shear are investigated. Prediction equations for ETSERF40-20 are developed, and are very useful for designing ER devices and vibration control. The shear modulus and yield strain increase as the electric field increases. Numerical hysteresis loops of ER fluids under different electric fields are then derived in order to determine the physical parameters used for vibration control. The prediction results show excellent agreement with measured results. A nonlinear empirical model of the dynamic behavior of electrorheological materials is developed. The electric field's dependence on the damping and stiffness of the absorber is studied: the equivalent damping and stiffness increase quickly with the electric field, but damping shows a tendency for saturation at very high electric fields. The control of vibration is considered here in terms of the ON-OFF strategy. The absorber efficiency is measured, and the results show that the ER dynamic absorber exhibits very good performances in terms of reducing the torsional vibrations of rotor systems. The smart absorber allows a 150% reduction in the vibration amplitude, and the minimum amplitude values can be reached when the electric field is applied between 1250 V/mm and 2000V/mm. These experimental results very closely approximate the simulation results. In fact, the results show that the SERDA's efficiency could be improved with an adaptive control strategy by varying the electric field with the frequency of excitation. This will be the object of a future work.

5.6 Acknowledgment

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CHAPITRE 6

SYNTHÈSE, CONCLUSIONS ET RECOMMANDATIONS

6.1 Synthèse

Le but principal de ce travail a été de développer un nouveau fluide ER, et d'étudier ses performances en faisant varier certains paramètres caractéristiques.

Dans la première partie (chapitres 3 et 4), un fluide ER qui a été nommé ETSERF, fabriqué avec des particules de diatomées a été développé. Les particules de diatomées ont été sélectionnées en raison de leurs structures spécifiques – structure en nid d'abeille cylindrique, ainsi que pour leurs autres caractéristiques – hautes capacités d'absorption, grande surface, haute stabilité chimique et faible densité de masse.

A l'aide de plans d'expériences, 288 essais ont été réalisés pour mesurer la contrainte de cisaillement. Le fluide ETSERF a été sélectionné, car il présente de très bonnes performances ER en comparaison avec les cinq autres fluides. Un surfactant peut être ajouté pour ralentir la sédimentation des particules du fluide malgré que l'efficacité des particules soit réduite un peu. De plus, les performances diélectriques et électro-rhéologiques sont fortement liées avec la durée du vieillissement. Une suspension ETSERF « fraîche » possède un haut taux de relaxation et une grande constante diélectrique, ce qui est dû à l'effet de la polarisation interfaciale. Les résultats expérimentaux montrent que la permittivité complexe du fluide ER dépend de la concentration de particules, de leur taille et de l'addition du surfactant, particulièrement dans le domaine des basses fréquences. L'étude des propriétés diélectriques permet de concevoir un ETSERF fluide plus efficace (l'effet de la permittivité, de la conductivité et de la fréquence de la relaxation). Il est montré que l'efficacité du fluide ER considéré pourrait augmenter en concevant un fluide avec les grosses particules hydratées avec une concentration en masse de particules inférieure à 28%.

De plus, nous avons proposé un nouveau modèle pour mieux décrire le comportement de ces fluides en régime dynamique. Une application est proposée afin de valider les performances et les modèles.

Un absorbeur dynamique ER a été conçu avec le fluide ER pour le contrôle des vibrations d'un système en torsion. La dépendance de l'amortissement et de la rigidité de l'absorbeur avec le champ électrique a été étudiée. Les valeurs minimums de l'amplitude de vibration ont été étudiées quand le champ électrique varie entre 1250 et 2000V/mm

6.2 Conclusions

Le plan d'expérience est un outil très puissant pour analyser l'interaction entre les paramètres qui ne sont pas connus en analysant un paramètre à la fois. L'analyse montre que la contrainte de cisaillement croît avec l'augmentation de la concentration des particules, de la taille des particules, et du champ électrique, mais il y a certaines exceptions. Les résultats obtenus montrent que :

1. **Concentration de masse** : afin d'éviter la saturation du composite, la concentration de masse ne peut pas dépasser une valeur critique qui est d'environ 28% pour ETSEF. Si une haute concentration de masse (environ 28%) était combinée avec des particules de grandes tailles (environ 40 μm), l'accroissement de la contrainte de cisaillement serait très élevé au début de l'application du champ électrique, et l'effet ER serait important dès que les chaînes sont formées.
2. **Champ électrique** : la contrainte de cisaillement croît avec l'augmentation du champ électrique et obéit à une loi polynomiale du deuxième ordre. En particulier, la réponse de la contrainte de cisaillement est très importante quand les fluides ER sont composés d'une grande concentration de grosses particules. Cependant, le champ électrique doit être supérieur à certains seuils de 1kV/mm dans notre cas afin d'obtenir de bonnes performances ER. C'est particulièrement important quand un fluide ER est utilisé à haute vitesse de cisaillement avec une forte concentration de particules. Le surfactant

affecte un peu les performances ER. Quand un surfactant est ajouté dans un fluide composé de grosses particules en haute concentration, un faible effet négatif se produit lorsque le champ électrique est élevé. La fréquence du champ électrique doit être inférieure à 10 Hz afin d'obtenir une haute constante diélectrique. Il est possible de contrôler la contrainte de cisaillement en variant la fréquence du champ électrique entre 10Hz et 100 Hz.

3. **Vitesse de cisaillement** : comme prévu, la contrainte de cisaillement croît avec la vitesse de cisaillement. Le champ électrique doit être élevé afin que les chaînes des particules se forment et obtiennent un effet significatif à haute vitesse de cisaillement.
4. **Taille et forme de particules** : la taille et la forme des particules sont d'autres facteurs importants qui influencent les propriétés du fluide ER. La contrainte de cisaillement augmente avec la taille des particules. Notamment, avec une grande concentration de grosses particules, l'accroissement de la contrainte de cisaillement est très significatif. Cet effet est augmenté quand le champ électrique est grand. Cependant, cette performance pourrait être légèrement affectée si un surfactant est ajouté. Le surfactant peut produire un effet négatif dans le cas où le fluide ER est préparé avec une haute concentration de grosses particules, un champ électrique élevé et une haute vitesse de cisaillement. La forme des particules affecte la performance du fluide ETSEF. Le fluide ETSEF20 (matériau obtenu par broyage) produit un faible effet ER en comparaison avec le ETSEF40 (non broyé), malgré qu'ils aient la même concentration de particules. C'est l'effet de la forme des particules, puisque la forme de particules de ETSEF20 a changé, certaines structures en nid d'abeilles sont brisées après avoir été broyées.
5. **Surfactant** : en général, l'effet ER de surfactant est faible. Il est utilisé pour que la sédimentation de particules soit ralentie. Il est recommandé pour contrer la sédimentation des particules, malgré qu'il produise parfois un faible effet négatif. De plus, l'effet ER du surfactant est positif pour les fluides ER avec les petites particules.

6. **Effet diélectrique** : Afin de comprendre le mécanisme d'action des particules, nous avons étudié les propriétés diélectriques des fluides ER avec leurs performances ER (deuxième article). En absence du champ électrique, le fluide ETSEF présente un comportement très proche de la loi de Newton. Cependant, le fluide manifeste une performance pseudo-plastique avec un seuil d'écoulement quand le champ électrique augmente, particulièrement pour le fluide ETSEF40. L'efficacité de l'ETSEF dépend fortement du comportement diélectrique du fluide. Les fluides ER humides possèdent une grande constante diélectrique, et un haut degré de relaxation. Le fluide contenant jusqu'à 0.3% d'eau (absorbée de l'air ambiant) montre un grand effet ER. Cela peut être expliqué par la polarisation inter-faciale qui contribue à l'augmentation de l'effet ER de ce fluide. Pour ces matériaux humides, la polarisation lente est prépondérante surtout pour des fréquences basses. L'analyse d'échantillons PMMA-particules est un outil fort utile pour comprendre l'action des particules. Plusieurs types de polarisations peuvent être invoqués pour expliquer le comportement du composite liquide (l'huile de silicone, particules de diatomées). On évoque souvent la polarisation de Debye ou de Maxwell-Wagner. Pour pouvoir décrire le comportement aux basses fréquences, il faut tenir compte de la conduction électrique des particules, ce que fait le modèle de Maxwell-Wagner. La relaxation diélectrique de Debye ne peut pas expliquer le phénomène diélectrique de nos fluides surtout aux basses fréquences et le modèle de Dissado-Hill introduit l'effet des agglomérations de particules. Cet effet peut expliquer le comportement diélectrique aux basses fréquences.

7. **Modélisation du comportement rhéologique**: basés sur le modèle de Bingham, deux modèles empiriques ont été développés pour modéliser nos fluides ETSEF. Afin de déterminer les constantes de nos modèles, une analyse ANOVA a été utilisée. Un de ces modèles est une fonction de multiples paramètres, il permet de prédire respectivement les seuils d'écoulement et la viscosité. Les valeurs prévues de la viscosité sont très proches des résultats expérimentaux sauf pour les vitesses de cisaillement très faibles. L'autre modèle, appelé Quasi-Bingham, est proposé afin de décrire la performance rhéo-fluidifiant du fluide. Le nouveau modèle constitue un gros

progrès par rapport au modèle de Bingham, et il donne un grand coefficient de corrélation. Le seuil d'écoulement obtenu avec modèle de Quasi-Bingham est plus raisonnable et précis en comparaison avec le modèle de Bingham.

8. **Comportement dynamique** : Étant donné que la performance viscoélastique du fluide ER est surtout importante à faible déformation et que le mécanisme élastique domine aux très basses vitesses de cisaillement, il est impossible de décrire le comportement du fluide sous une excitation mécanique en utilisant le modèle de Bingham. Par conséquent, afin de comprendre les performances dynamiques du fluide ER, un modèle plus général du type Quasi-Bingham est proposé dans le troisième article, basé sur le modèle qui est développé dans le deuxième article. La solution numérique du cycle d'hystérésis du fluide ER qui est obtenue en utilisant le « Général Quasi-Bingham » sous différents champs électriques montre un excellent accord avec les mesures. Une équation prédictive a été obtenue pour l'ETSERF40-20. Cette équation est très utile dans la conception du fluide ER et pour le contrôle des vibrations. Les caractéristiques dynamiques du fluide ER sous une excitation vibratoire sont analysées. Le module de cisaillement et la déformation plastique augmentent avec le champ électrique. L'amortissement et la rigidité équivalents (définie dans le domaine plastique) augmentent rapidement avec le champ électrique jusqu'à une saturation.

6.3 Recommandations

On a utilisé seulement une stratégie simple de contrôle semi-actif 'on-off' dans cette étude. Il sera intéressant d'étudier la commande de l'absorbeur SERDA pour réaliser un système de contrôle adaptatif. Les perspectives de ce travail consistent donc d'abord à développer et simuler un algorithme semi-actif du contrôle des vibrations d'un rotor basé sur le modèle de Général Quasi-Bingham. Ensuite, il faudrait valider les résultats numériques obtenus, et autant que possible, re-modéliser le système pour améliorer l'absorbeur. En plus, il sera important de continuer à travailler sur la modélisation de fluide ER. Actuellement on n'a pas

encore trouvé un modèle parfait pour décrire tous les fluides ER, malgré les fluides rhéofluidifiants.

ANNEXE I**ARTICLES DE CONFÉRENCE****CANSMART 2004****Investigation of Dynamic Behavior of Electrorheological Fluids by Experimental Design**

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ABSTRACT

An electrorheological (ER) fluid presents an apparent viscosity which increases when an electric field is applied, and can restore its property when the field is removed. An ER fluid consists of a suspension of micron-sized particles dispersed in a dielectric liquid. Subjected to an electric field, many particle chains are formed between the electrodes, causing a resistance to flow (flow mode) or to the shear movement of electrodes (shear mode). ER fluids commonly behave like Bingham fluids under applied fields, but however exhibit the characteristics of a quasi-Newtonian fluid when the applied electric field is turned off. Reversible change of viscosity occurs in milliseconds with the fields applied. Therefore the fluids are suitable for the real-time control of vibration, structural vibration damping, etc. However, its applications are limited due to the sedimentation of the particles. Viscous performance can vary with the shape, size, and the concentration of particles, as well as with the density ratio of the fluid to the particles. To understand the effect of design parameters on viscosity, an experimental design was performed on a home-made ER fluid, using as independent variables electric field strength, particle concentration, surfactant content, particle size, and shear rate. The influence of the shear rate on shear stress was analysed with the electric field strength applied and particle concentration imposed. The results of this study can be used to develop an optimized ER fluid for vibration control.

INTRODUCTION

The electrorheological(ER) fluid is a type of liquid composed of polarisable particles suspended in the liquid dielectric, and whose rheological properties change when an electric field is applied. These behaviours are sensitive to the electric field applied. Under a suitable external electric field, ER fluids can transform between the liquid and quasi-solid states. This reversible effect happens within milliseconds [1]. The ER phenomenon was first described by Winslow in 1949[2]. Particularly, ER fluids are characterised by a high shear stress, a fast response time (in milliseconds), and a low current component. ER fluids can be used to control the force in minimized products through the application of a high electric field. It can be used as an interface between a mechanical and an electronic system to realize an automatic control process.

In the last two decades, ER fluids have fascinated many scientists, engineers, and inventors. Many industrial products have been developed using ER fluids, such as, vibration insulators, shock absorbers, clutches and damping devices [3-6]. However, ER-fluid applications and corresponding marketing have remained limited mainly because: 1) their behaviours are complex and non-linear; 2) devices using ER fluids need high voltages to supply the very high electric fields within them; and 3) particle sedimentation is a severe problem in ER fluids. Currently, researchers and engineers are trying to find an ER fluid that can overcome all these problems, but that is very difficult to realize since the performances of the fluids ER depend not only on the combination of fluid and particles in the ER fluid but also on many factors such as the shear rate, the electric field, and the surfactant content. The experimental design can provide a statistical analysis for use in evaluating the parametric effect in a system using a series of experiments. In addition, this method can also determine the interactions within various parameters [7].

In this article, we use the Design of Experiment to study and observe the influences of particle concentration, particle size, surfactants, the electric field, and shear rate on ER fluid properties, with a view to finding an optimal ER fluid and an empirical model for predicting the dynamic behaviours of ER fluids.

EXPERIMENTAL DESIGN

ER fluid behaviours depend mainly on the concentration of particles in liquid, electric field, shear rate, surfactant, and particle size factors. A ‘Multilevel factorial’ design was selected to determine two-level interactions between the independent variables, as is indicated above. For rheological measurements of ER fluids, a cylindrical rotary viscometer (Couette) was developed and used in these tests. This viscometer was designed and manufactured according to ISO 3219. It combines the speed control system and TREK high-voltage Amplifier/Supply. The studied fluid is filled between the two coaxial cylinders. The laminar movement of shearing of the ER fluid is obtained by the rotation of the inner cylinders, which has various uniform rotational angular velocities, and with the outer cylinder remaining motionless. The design parameters of the twelve studied ER fluids are shown in Table 1. For this design, 144 tests were required. We carried out 2 repetitions (288 trials) in order to

increase the confidence. An analysis of variance (ANOVA) is used to analyse the data collected for investigating the main effects of particle concentration, particle size, surfactant, electric field, and the shear rate, as well as their corresponding two-level interaction effects on the dependent variables. The STATGRAPHICS Plus 5.0 software application was used to perform the ANOVA analysis.

Table 1 Levels of independent variables

Variable	Unit	level 1	level 2	level 3	Level 4
Design parameters					
Particle mass Concentration	%	15	20	25	
Mean size of particles	μm	41	68		
Surfactant	PPM	0	90		
Operational parameters					
Electric field	kV/mm	0	1	2	
Shear rate	1/s	92	277	462	647

RESULTS AND DISCUSSIONS

We observed the main effects and interactions of independent variables on the shear stress (Pa). The results are shown in Fig. 1.

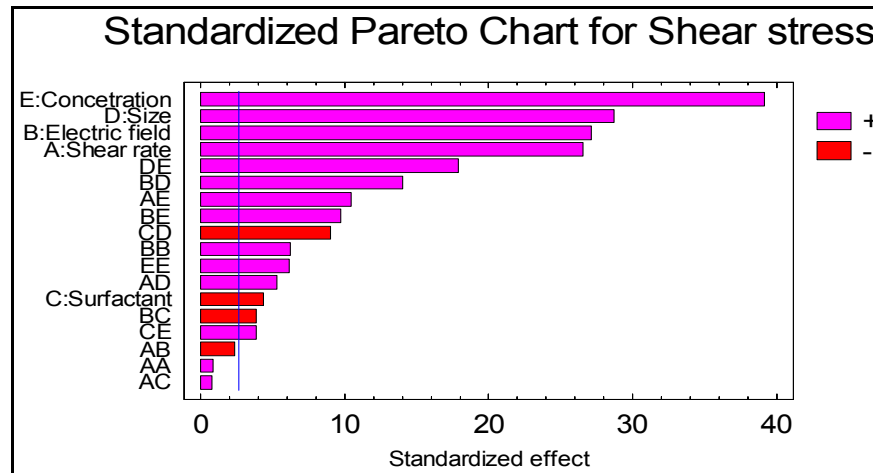


Fig 1. Standardized Pareto chart for shear stress

The Pareto diagram shows that the electric field (B), the concentration (E), the surfactant (C), the shear rate (A), the particle size (D), the interactions of DE, BD, AE, BE, CD, AD, BC, and CE are significant at the 99% confidence level. Based on the results here, we can eliminate the AA, AB and AC effects. Therefore, to simplify the study, we consider only the parameters which strongly influence the ER fluid properties.

Effect of parameters on shear stress

The shear stress (Pa) was considered as the dependent variable. For the data analysis, we selected the 0.01 confidence level for testing the significance of the main effects and two-level interaction effects. An analysis of variance (ANOVA) was applied to investigate the main effects of particle concentration, particle size, surfactant, electric field, shear rate, and their corresponding two-level interaction effects on shear stress. The computer ANOVA output and the calculated F ratios are shown in Table 2 for each significant effect. All F ratios are based on the residual mean square error. The ANOVA table decomposes the variability of shear stress into contributions due to various factors. Type III sums of squares were chosen. 13 P values are less than 0.01, and these factors have a statistically significant effect on shear stress at the 99 % confidence level.

Table 2 Analysis of Variance for Shear stress

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Shear rate	96252	3	32084	256	0,0000
B:Electric field	105393	2	52696	420	0,0000
C:Surfactant	2545	1	2545	20	0,0000
D:Size	112232	1	12232	894	0,0000
E:Concentration	213565	2	106782	851	0,0000
INTERACTIONS					
AD	3824	3	1274	10	0,0000
AE	15293	6	2548	20	0,0000
BC	2031	2	1015	8	0,0004
BD	29333	2	14666	117	0,0000
BE	13639	4	3410	27	0,0000
CD	11065	1	11065	88	0,0000
CE	2100	2	1050	8	0,0003
DE	44855	2	22427	179	0,0000
RESIDUAL	32123		256	125	

TOTAL (CORRECTED)	684249	287			

Shear stress effect induced by the interaction between the particle concentrations and shear rate/electric field/surfactant/particle size

Figures 2, 3, 4, and 5 show the results for the shear stress affected by the interactions of the concentration and the shear rate, the concentration and the electric field, the concentration and the surfactant, and the concentration and the particle size, respectively. In these figures, it can be seen that the shear stress increases with an increase in particle concentration. The in-

creasing effect is more significant with high shear rates, high electric fields, and large particle sizes. However, the shear stress decreases with an increase in the amount of surfactant added to an ER fluid.

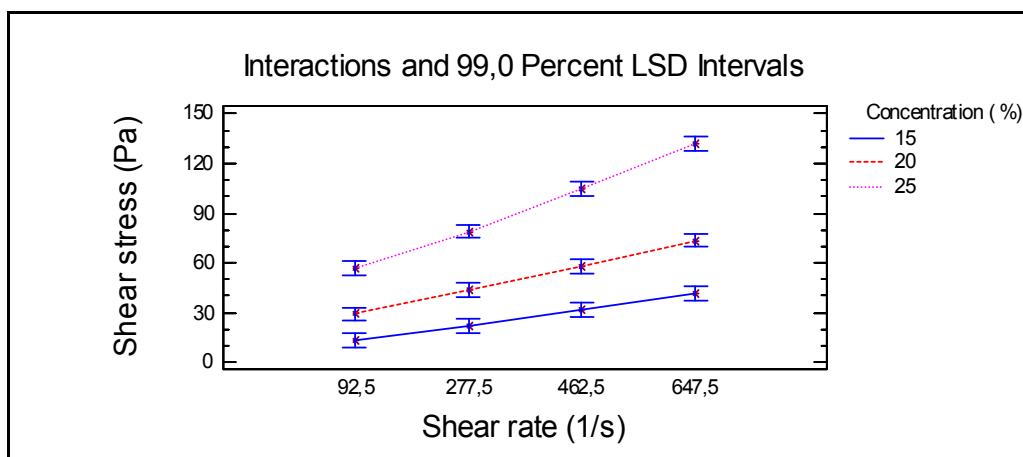


Fig 2. Interaction effect of concentration and shear rate on shear stress

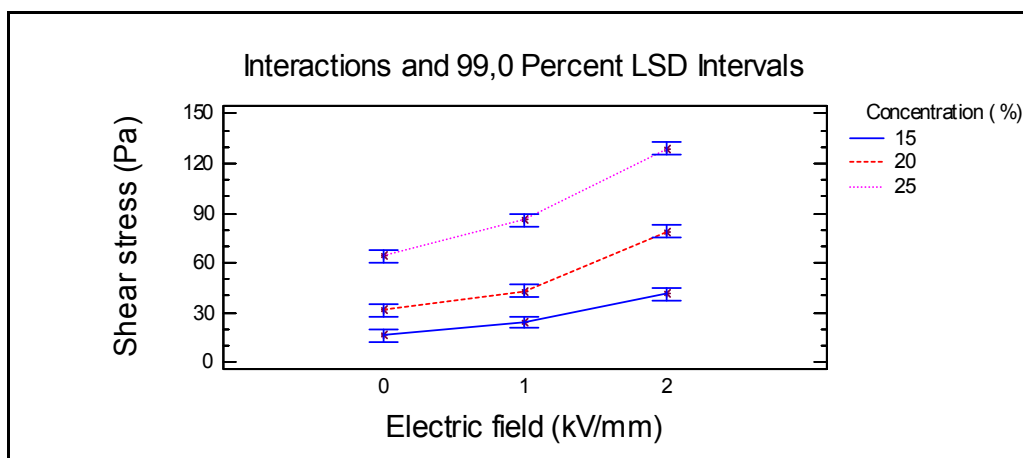


Fig 3. Interaction effect of concentration and electric field on shear stress

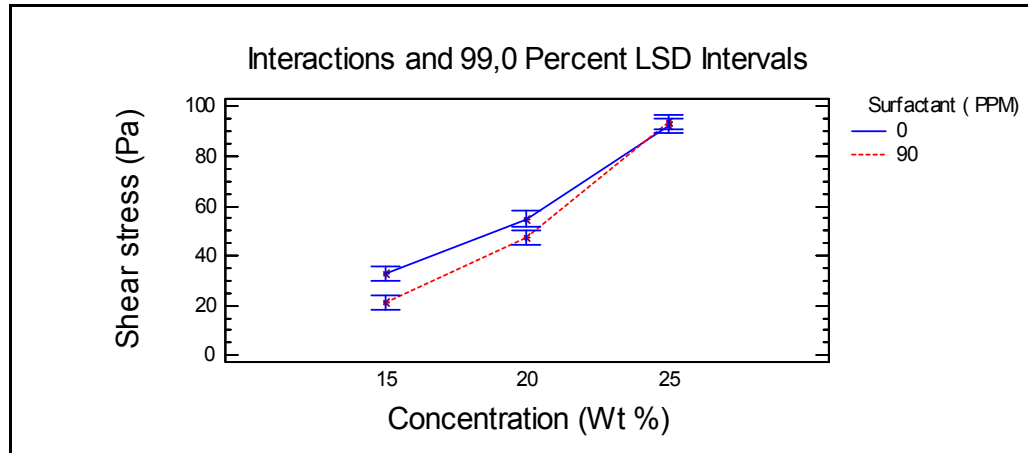


Fig 4. Interaction effect of concentration and surfactant on shear stress

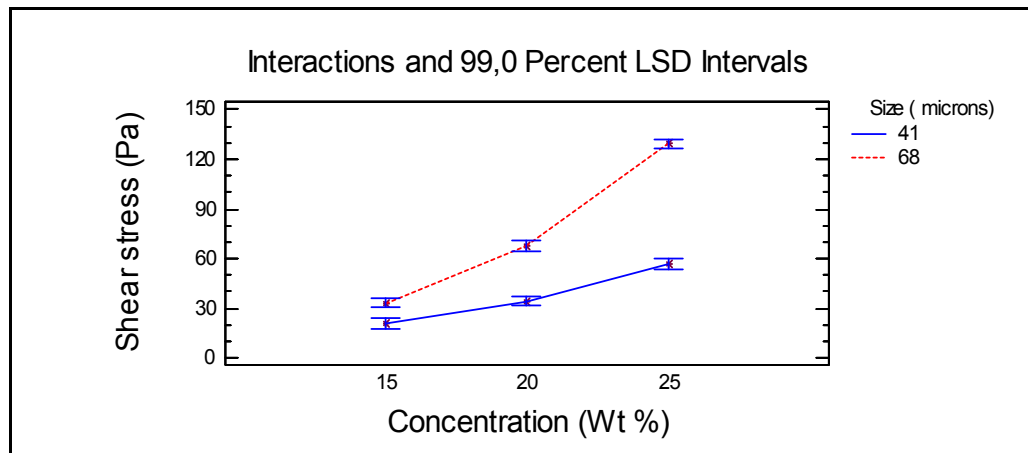


Fig 5. Interaction effect of concentration and size on shear stress

Shear stress effect induced by the interaction between particle size and surfactant/electric field/shear rate

Figures 6, 7, and 8 show the shear stress results affected by the interactions of the particle size and the surfactant, the particle size and the shear rate, and the particle size and the electric field, respectively. The shear stress increases with an increase in particle size for all cases. The increasing effect is more significant at high shear rates and high electric fields. However, the shear stress increases a little slowly when the surfactant is added to the ER fluid. In addition, the shear stress becomes larger when a surfactant is added to the ER fluid using small particles.

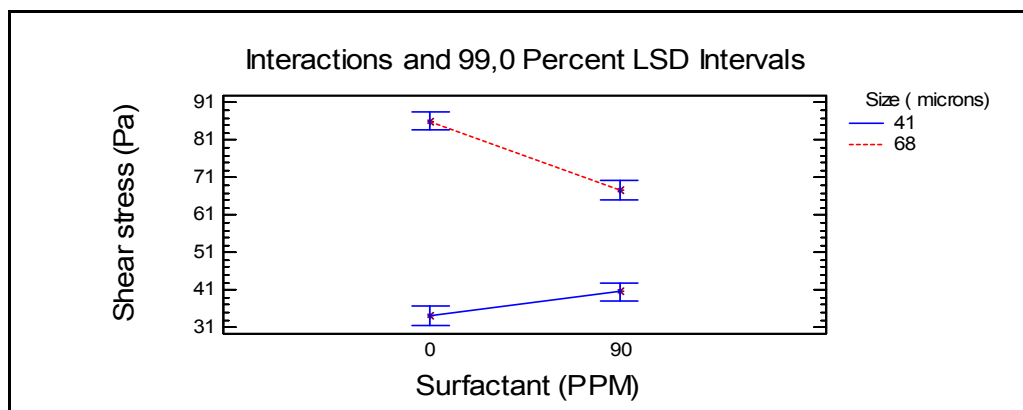


Fig 6. Interaction effect of size and surfactant on shear stress

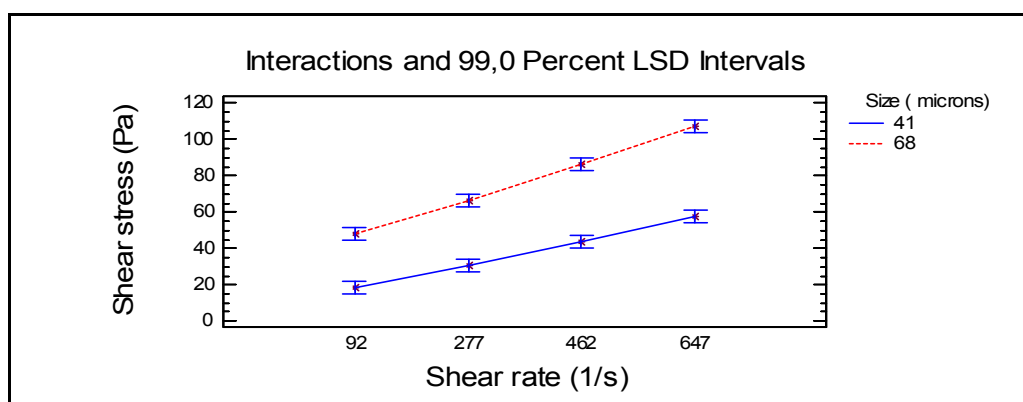


Fig 7. Interaction effect of size and shear rate on shear stress

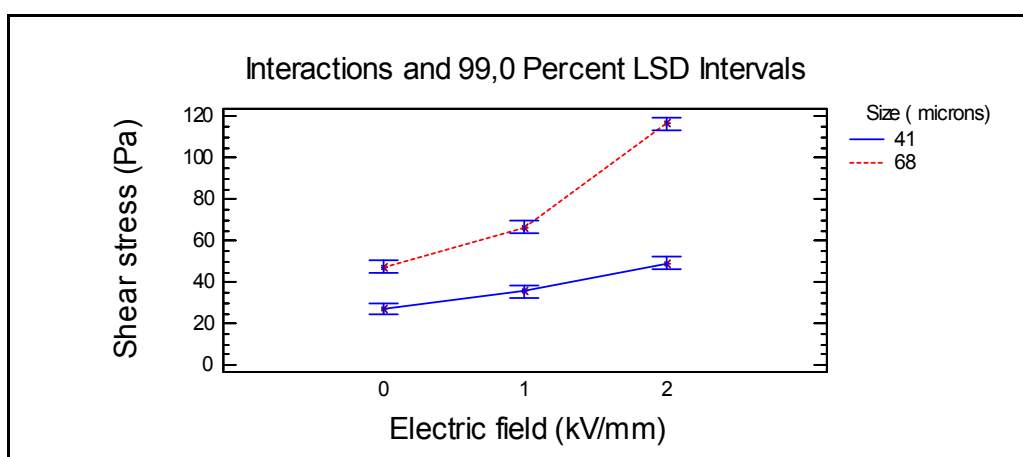


Fig 8. Interaction effect of size and electric field on shear stress

Shear stress effect induced by the interaction between surfactant and electric field

Fig 9 shows the result for the shear stress induced by the interaction of the electric field and the surfactant. The shear stress decreases with an increase in the amount of surfactant added to the ER fluid when the electric field is applied. The decreasing effect is more significant with a high electric field.

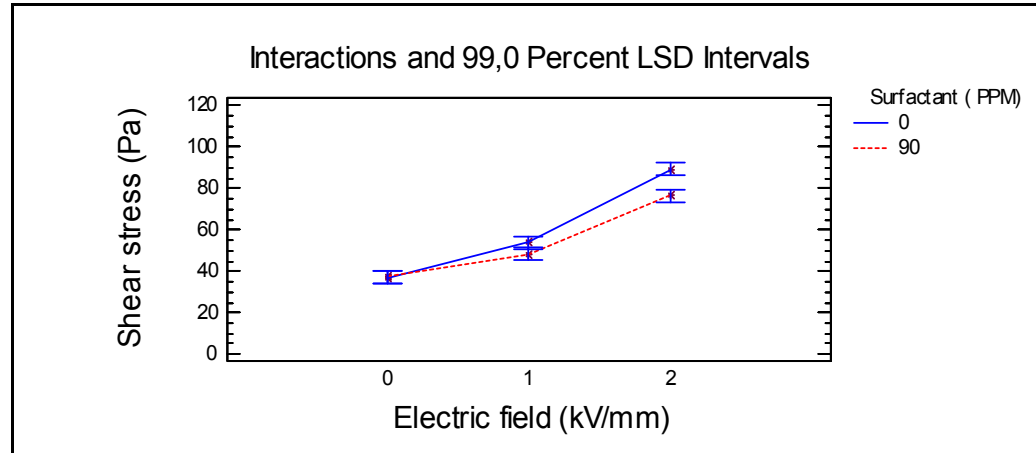


Fig 9. Interaction effect of surfactant and electric field on shear stress

Experimental model for shear stress

Based on the results in this study, an optimal ER fluid can be chosen to meet specific needs. For example, we chose large particles and no surfactant for a high shear stress, in which case, the ER behaviour depends mainly on the particle concentration, electric field, and shear rate.

Applying a regression to these data and considering the significant variables, we can obtain an experimental model of the shear stress for our case. In order to develop a model, we have conducted a multiple regression analysis. Results are shown in Table 3.

The output shows the results of fitting a multiple linear regression model to describe the relationship between the shear stress and 6 independent variables. The equation of the fitted model is:

$$\tau = (16.2E^2 - 41.9E + 0.25\phi^2 - 4.9\phi + 2.6E\phi) + 0.006\phi\dot{\gamma} \quad (1)$$

$$\tau = \tau_c + \eta\dot{\gamma}$$

Here, τ is the shear stress, τ_c is the yield, η is the dynamic viscosity, ϕ is the mass concentration of particles, and E is the electrical field.

The values of the variables are specified in their original units, as is indicated in Table 1.

If we consider an approximate Bingham-model, the viscosity and the yield stress can be modeled as:

$$\tau_c = 16.2E^2 - 41.9E + 0.25\phi^2 - 4.9\phi + 2.6E\phi \quad (2)$$

$$\eta = 0.006\phi \quad (3)$$

Since the P-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level.

Table 3 Multiple Regression Analysis

Dependent variable: Shear stress					

	Standard	T			
Parameter	Estimate	Error	Statistic	P-Value	

Electricfield	-41,9	10,6	-3,9	0,0002	
Concentration	-4,9	0,65	-7,5	0,0000	
Electricfield^2	16,2	3	5,3	0,0000	
Concentration^2	0,25	0,03	8,6	0,0000	
Shearrate*Concent	0,006	0,0003	17,6	0,0000	
Electricfield*Con	2,5	0,4	6	0,0000	

Analysis of Variance					

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value

Model	787599	6	131267	876	0,0000
Residual	9888,7	66	150		

Total	797488		72		
R-squared = 98,76 percent					
R-squared (adjusted for d.f.) = 98,67 percent					
Standard Error of Est. = 12,24					
Mean absolute error = 9,48					

The R-squared statistic indicates that the model as fitted explains 98.76% of the variability in shear stress. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 98.67 %. The standard error of the estimate shows the standard deviation of the residuals to be 12.2. The mean absolute error (MAE) of 9.4 is the average value for residuals.

In determining whether the model can be simplified, we note that the highest P-value of the independent variables is 0.0002, falling under *Electric field*. Since the P-value is less than 0.01, the highest order term is statistically significant at the 99% confidence level. Consequently, we do not have to remove any variables from the model. Fig 10 shows the predicted values from our new model with the observed data.

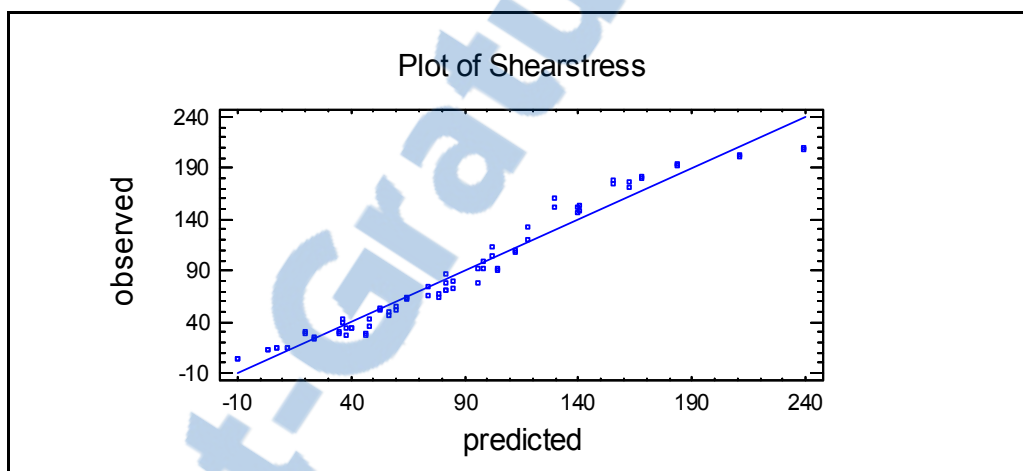


Fig 10. Observed data versus predicted values

Conclusion

This work shows the results of an experimental design conducted on 288 shear stress measurements, and an experimental model for a specific ER fluid was developed. The experimental design results show that shear stress increases with an increase in particle concentration, particle size and electric field in the studied range. As expected, shear stress will increase with a high electric field, but the increase is less effective when a surfactant combined with a very high electric field are added. Our results also show that the experimental design method is a powerful tool for analysing interactions between parameters that cannot be seen by analyzing one parameter at a time. It is a useful tool for optimizing an ER fluid and for obtaining useful experimental models for practical usage, as well as for gaining multi-parameter influences and interaction between parameters.

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AMORTISSEMENT DES VIBRATIONS DE TORSION DE ROTORS À L'AIDE DE FLUIDES ÉLECTRO-RHÉOLOGIQUES

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RÉSUMÉ :

Les fluides électro-rhéologiques (ER) sont composés de fines particules solides en suspensions dans un liquide diélectrique isolant. Leur comportement rhéologique est fortement influencé par le champ électrique appliqué qui produit un alignement des particules et la formation de chaînes. On a pu ainsi observer une très forte augmentation de la viscosité apparente. Le changement de viscosité est rapide et réversible sous l'influence d'un champ électrique. Les applications potentielles sont nombreuses, surtout dans le domaine de contrôle des vibrations. Le contrôle semi-actif des vibrations de structures en utilisant les fluides ER a suscité un grand intérêt pour les chercheurs car il combine les avantages des systèmes passifs avec les avantages du contrôle actif. Introduit judicieusement dans une structure, le fluide ER peut jouer un rôle d'amortisseur. Son amortissement peut varier selon le champ électrique appliqué. L'utilisation de fluides ER dans le contrôle de vibrations des arbres en torsion est observée dans cette étude. Pour réduire la transmissibilité des vibrations de rotors flexibles excités harmoniquement en torsion, on doit introduire de l'amortissement lorsque le rotor opère proche des fréquences naturelles comme lors de montées (ou descente) en vitesse. Par contre l'amortissement s'avère préjudiciable lorsque le rotor opère au-delà de la fréquence naturelle (rotors flexibles). En conséquence, il est nécessaire d'employer un amortissement qui varie afin d'optimiser la transmissibilité. Le système ER peut fournir un amortissement de torsion variable en réponse à un champ électrique. Une simple stratégie *on-off* de contrôle d'amortissement basé sur le rapport de fréquence d'excitation/ fréquence naturelle est utilisé dans un contrôle en boucle ouverte. Des simulations théoriques sont conduites afin d'étudier les effets de la force du champ électrique sur l'amortissement. Un modèle est proposé afin de simuler par Matlab, un système semi-actif et le contrôle de la transmissibilité est optimisé sur une grande gamme de fréquence.

1.0 INTRODUCTION

L'effet électrorhéologique (ER), décrit pour la première fois par Winslow en 1949 (Winslow 1949), correspond au phénomène de modification de la viscosité d'un fluide lorsqu'on lui applique un champ électrique. Les fluides ER sont souvent des suspensions de fines particules diélectriques dans un liquide isolant. Leur comportement rhéologique est fortement influencé par le champ électrique appliqué qui produit un alignement des particules et la formation de chaînes. On a pu ainsi observer une très forte augmentation de la viscosité apparente.

Depuis les 50 dernières années, des fluides qui répondent mécaniquement à la stimulation électrique ont été développés. Ces fluides ER montrent un effet rapide, et réversible et se manifestent par la transition d'un état liquide à un état quasi-solide sous un champ électrique extérieur (Phule and Ginder 1998). Des propriétés particulières des fluides ER sont leur haute contrainte de cisaillement, la basse densité du courant et un temps de réponse qui est de l'ordre de la milliseconde. Le fluide ER peut être utilisé pour contrôler une force par un champ électrique important. On peut utiliser ces fluides dans des conditions extrêmes grâce à leur durée de vie élevée et leur capacité pour fonctionner dans un grand intervalle de température.

Les applications potentielles des fluides ER sont nombreuses. Ils peuvent être employés pour le contrôle et l'atténuation de vibrations, sous l'application d'un haut champ électrique. Ils peuvent être employés comme une interface entre les systèmes mécaniques et électroniques pour réaliser un procédé de contrôle automatique en temps réel (Block and Kelly 1988; Stanway, Sproston et al. 1996; Choi and Kim 2000). Certains produits ont été développés comme isolateur de vibrations et absorbeur de choc (Sassi, Chérif et al. 2003), embrayages, freins (Furusho, Sakacuchi et al. 2001; Oualla, Thomas et al. 2003), amortissement structural (Choi SB, Bang JH et al. 2002), amortissement sismique [11], etc.

La nécessité de systèmes de contrôle à la fois, fiables et robustes, comme le contrôle passif et, efficaces et commandables, comme le contrôle actif, a motivé récemment le développement de systèmes de contrôle semi-actifs, utilisant dans le même traitement les matériaux passifs et actifs. Le premier assure la fiabilité et la robustesse du système puisqu'en cas de mauvais fonctionnement du contrôle actif, le système reste amorti. Le second améliore les performances sans affecter la sécurité. Depuis les années dernières, le contrôle semi-actif des vibrations de structures par l'utilisation de fluides ER a suscité un grand intérêt pour les ingénieurs et les chercheurs, car il combine les avantages des appareils passifs avec les avantages du contrôle actif et il n'a pas besoin de grande énergie externe comme le système du contrôle actif. Choi et al [4] ont proposé un type d'amortisseur ER cylindrique. Kamath et al [12] ont proposé un modèle analytique pour la prédiction de la force d'amortissement dépendant du champ électrique. Comme le fluide ER est considéré de type intelligent, de par ses capacités d'adaptation rapide facilement contrôlables, il peut aussi être utilisé dans le contrôle des vibrations de rotors.

Dans cette étude, nous avons développé un amortisseur ER qui travaille en mode de cisaillement pour réaliser le contrôle semi actif des vibrations de torsion d'un rotor.

2.0 Transmissibilité des vibrations de torsion

Dans cette étude, nous avons étudié l'amortissement de vibrations de torsion de rotors. Si on modélise le rotor comme un système à un seul degré de liberté de torsion, il peut être représenté par une inertie de rotation J , un ressort de torsion K_t et un amortisseur de torsion C_t (généralement très faible). Le module de la transmissibilité des rotations peut s'écrire comme suit :

$$TR = \frac{\theta}{\theta_0} = \frac{\sqrt{1 + (2\zeta\gamma)^2}}{\sqrt{(1 - \gamma^2)^2 + (2\zeta\gamma)^2}} \quad (1)$$

et la phase entre la rotation transmise θ et la rotation émise θ_0 est égale à :

$$\psi = \tan^{-1}(2\zeta\gamma) - \tan^{-1}\left(\frac{2\zeta\gamma}{1 - \gamma^2}\right) \quad (2)$$

où $\gamma = \omega/\omega_n$

ω est le fréquence d'excitation,

ω_n est le fréquence naturel du système,

ζ est le taux d'amortissement.

La figure 1 montre l'amplitude de la transmissibilité (équation 1) en fonction du taux d'amortissement de la fréquence.

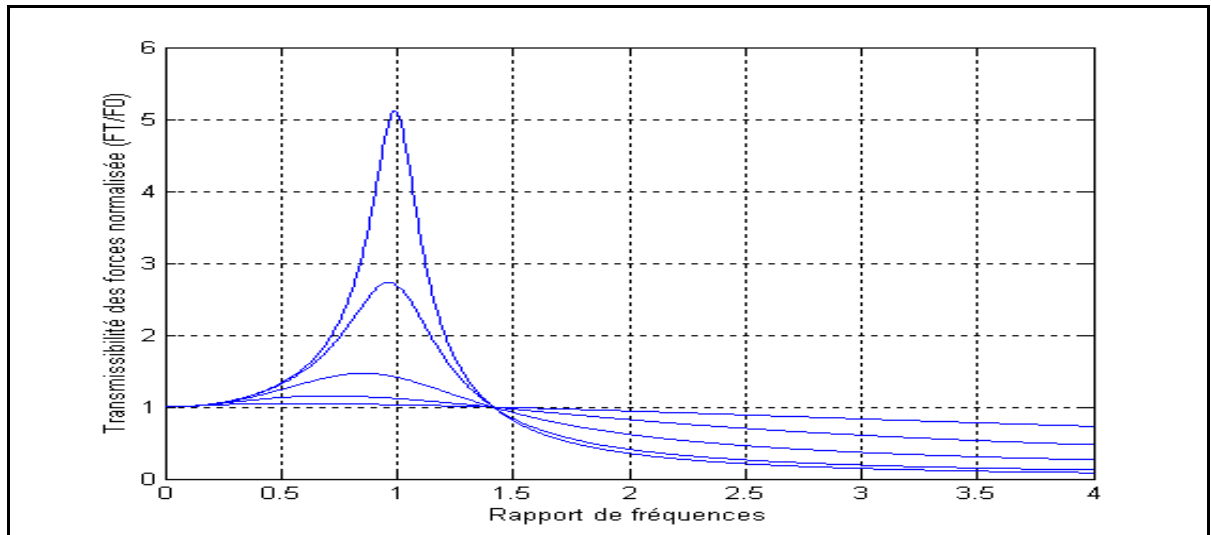


Figure 1 Transmissibilité des vibrations

On peut constater que l'amortissement n'est avantageux que proche des résonances, mais qu'il est néfaste pour des fréquences d'excitation nettement supérieures à la fréquence de résonance (structures flexibles) [13]. En fait, la figure 2 montre qu'il faudrait faire varier l'amortissement de maximal proche des résonances à minimal pour des fréquences d'excitation supérieures à 1.4 fois la résonance.

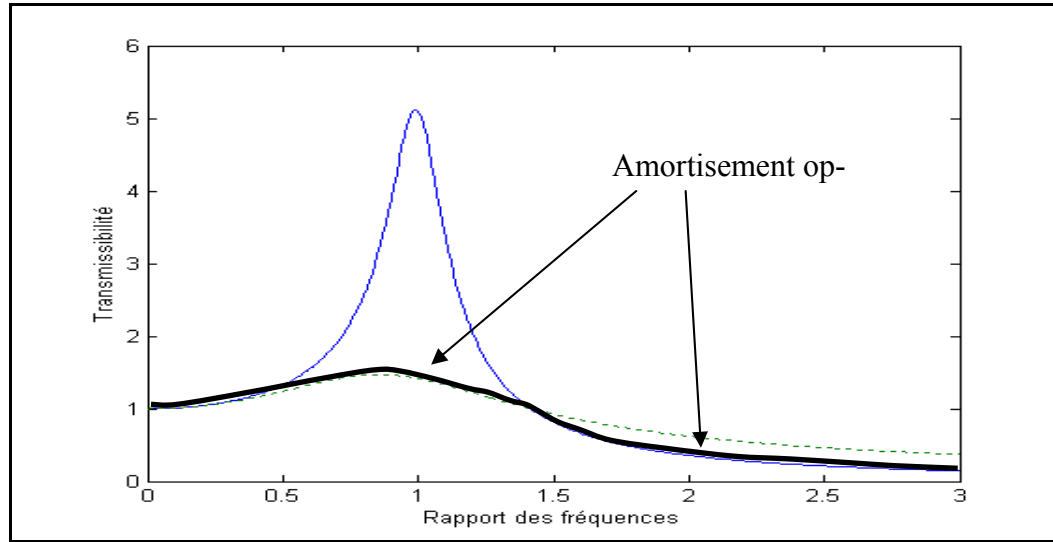


Figure 2 Amortissement optimal

Un amortissement passif n'est pas capable de réaliser cet objectif et on doit faire appel à un amortissement adaptable, comme peut le faire le fluide ER.

Voici donc le principe de contrôle semi-actif *on-off* des vibrations que l'on propose. Quand la fréquence de la force d'excitation est proche de la fréquence naturelle du système, l'amortissement du système est augmenté en appliquant un champ électrique. Par contre, lorsque le système fonctionne dans la zone $\gamma = \omega/\omega_n > 1.41$, l'amortissement du système mis au minimum en n'activant pas le champ électrique.

3.0 COMPORTEMENT RHÉOLOGIQUE DU FLUIDE ER EN MODE DE CISAILLEMENT

En général, les comportements rhéologiques de la plupart des fluides ER répondent au modèle de Bingham quand le champ électrique est appliqué [14].

$$\tau = \tau_c + \eta_\infty \dot{\gamma} \quad (3)$$

où τ est la contrainte de cisaillement résultante (Pa)

τ_c est le seuil d'écoulement (Pa)

$\dot{\gamma}$ est la vitesse de cisaillement (1/s)

η_∞ est la viscosité dynamique réelle du mélange (Pa. s) à une vitesse infinie.

Le premier terme représente une force de friction, alors que le deuxième représente une force visqueuse. Toutefois, ce modèle n'est qu'approximatif, surtout pour de basses vitesses de cisaillement.

Dans cet article, nous proposons un nouveau modèle non-linéaire qui est appelé modèle de **Quasi-Bingham**. Ce modèle peut être formulé comme suit :

$$\tau = \tau_c + \eta_\infty \dot{\gamma} + (\eta_0 - \eta_\infty) \frac{\dot{\gamma}}{1 + (t\dot{\gamma})^n} \quad (4)$$

où η_0 est la viscosité dynamique à basse vitesse.

t est un paramètre temporel relié au mélange

n est un exposant relié au mélange.

Le mécanisme pseudo-élastique du fluide ER est bien décrit avec ce modèle.

4.0 MESURES DU COMPORTEMENT RHÉOLOGIQUE

Système de mesure du fluide ER

Un viscosimètre rotatif cylindrique Couette a été développé et modifié pour appliquer le champ électrique (figure 3). Ce viscosimètre est conçu et fabriqué selon norme ISO 3219(ISO 1993). Il combine un système de contrôle de vitesse et un système de génération d'un champ électrique de haut voltage (10kV) afin de réaliser une mesure automatique. Le fluide étudié est rempli entre les deux cylindres coaxiaux. Le mouvement laminaire du fluide ER en cisaillement est obtenu par la rotation du cylindre intérieur à diverses vitesses angulaires de rotation uniforme.

Il a d'abord été utilisé pour la mesure de la contrainte de cisaillement. Le cylindre externe est libre de tourner, mais applique une force sur une poutre flexible équipée d'une jauge de contrainte.

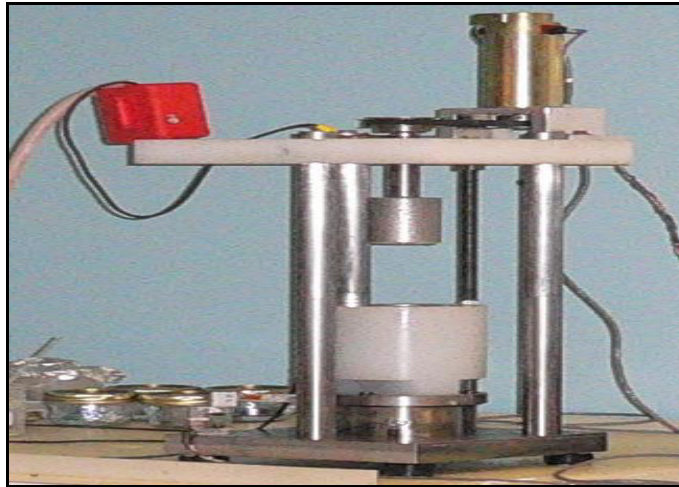


Figure 3 Système de mesure

4.2 Réponses rhéologiques du fluide ER en mode de cisaillement

Le tableau 1 montre les résultats d'une simulation numérique du modèle de Quasi-Bingham montré à l'équation (4) et appliqué au fluide ETSERF 20-28, développé par nos soins.

Type de fluide ER	E (kV/mm)	t	n	τ_c	η_0	η_∞	$\eta_0 - \eta_\infty$	S	R^2
ETSERF20-28	0		0	4.851	0.3145	0.3145	0	77.61	0.9987
	1	0.02	1.26	40.4775	1.3733	0.2947	1.0786	15.17	0.9997
	2	0.015	0.97	125.2249	1.9545	0.2982	1.6563	14.03	0.9999

Table 1. Paramètres théoriques du fluide ETSERF 20-28 en mode de cisaillement

La figure 4 montre les rhéogrammes théoriques superposés à ceux mesurés. La concordance du modèle développé avec les valeurs a montré des coefficients de détermination R^2 supérieurs à 99%.

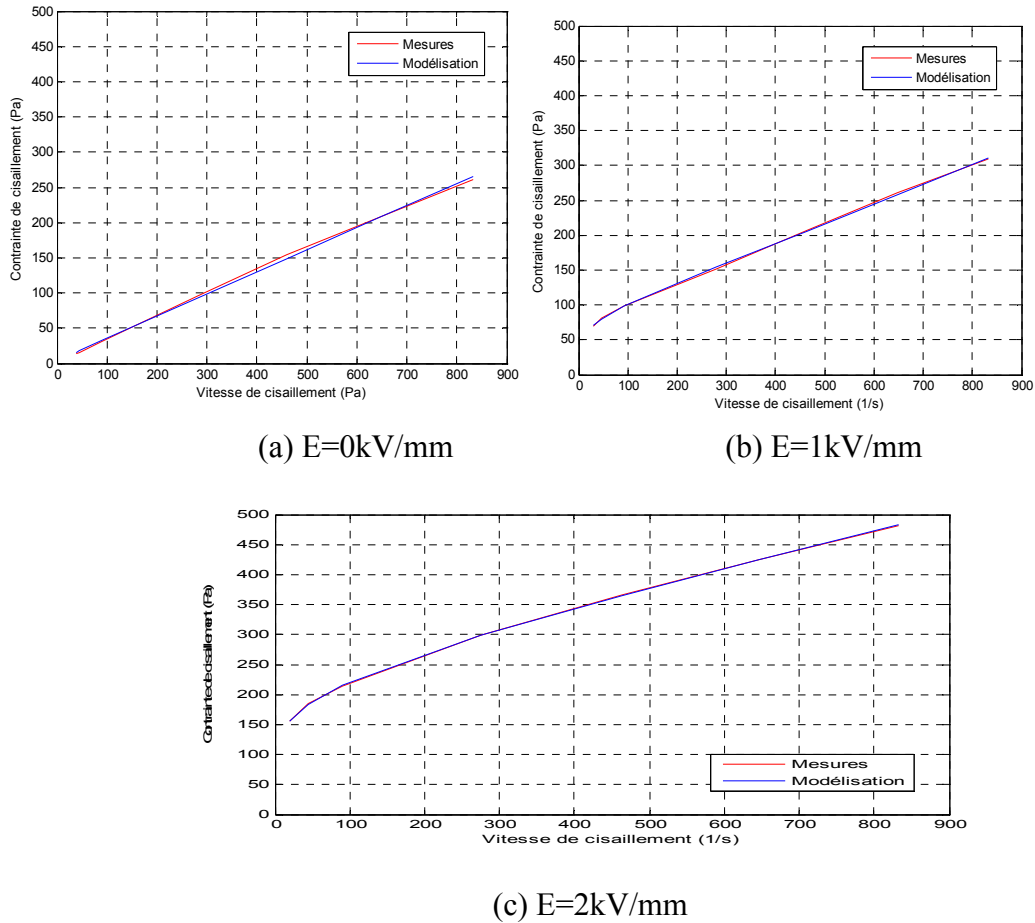


Figure 4. Comparaison des rhéogrammes théoriques et expérimentaux du fluide ET-SERF20-28 en fonction du champ électrique.

5.0 MESURE DE L'AMORTISSEMENT DU FLUIDE ER EN MODE DE CISAILLEMENT

La mesure d'amortissement a été appliquée sur le viscosimètre de Couette modifié pour appliquer le champ électrique (figure 5).

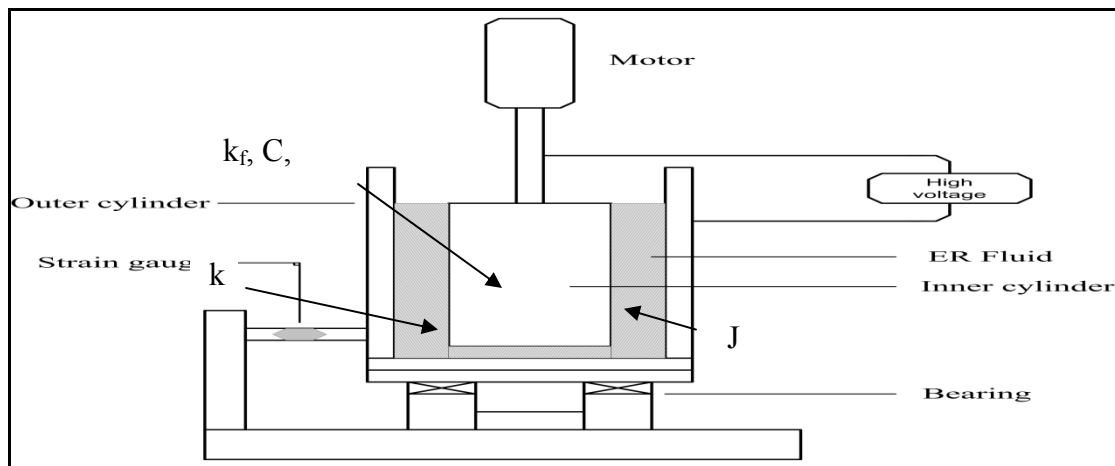
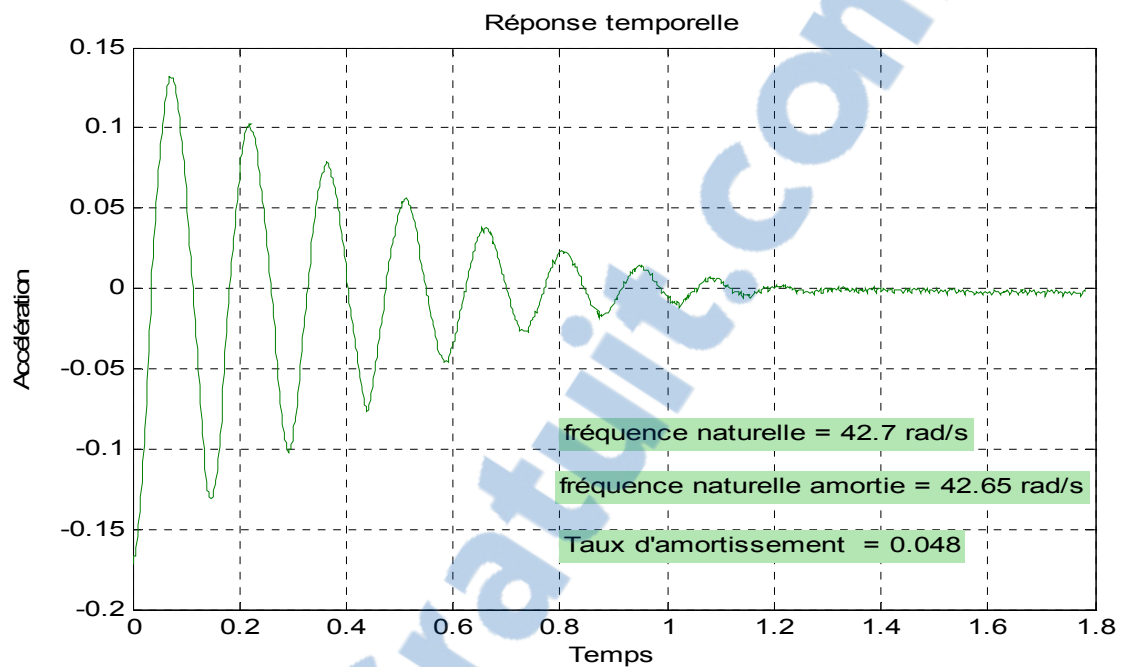


Figure 5 Système de mesure d'amortissement

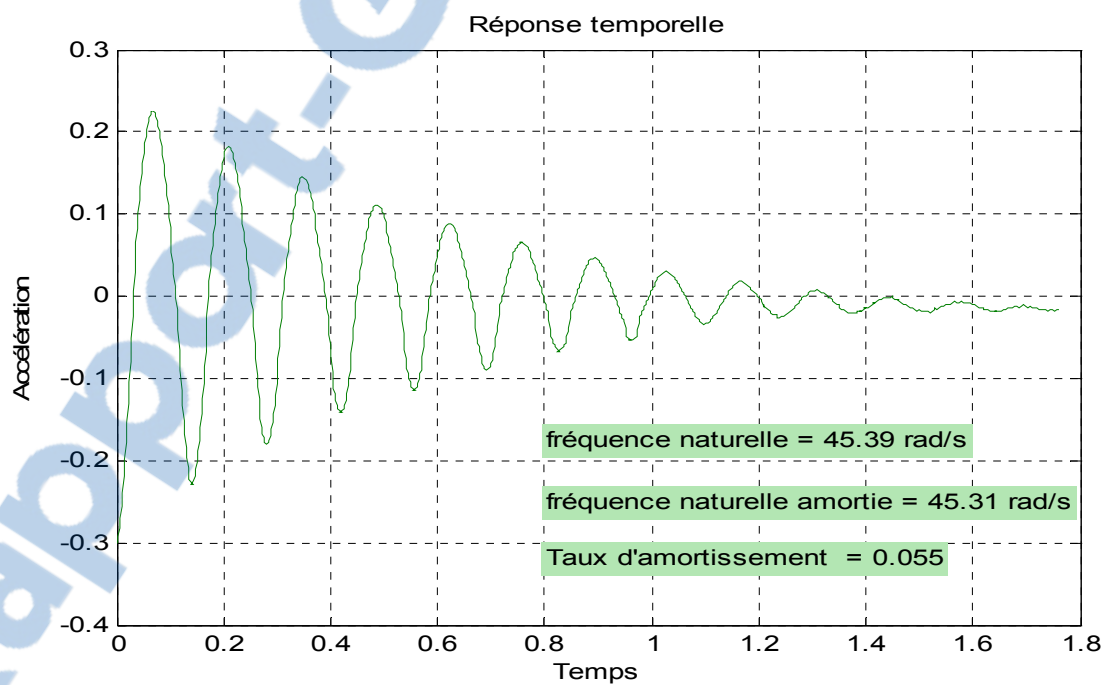
Pour la mesure d'amortissement procuré par le fluide ER, nous avons fixé le cylindre intérieur du rhéomètre et mis un accéléromètre sur le cylindre extérieur. La poutre flexible sur laquelle appuie le cylindre externe peut être considérée équivalente à un ressort de torsion. L'accéléromètre a été positionné le long de la tangente du cylindre extérieur, pour mesurer la composante de rotation. La mesure de la valeur du ressort de torsion k_p a donné 7.73 N.m/rad.

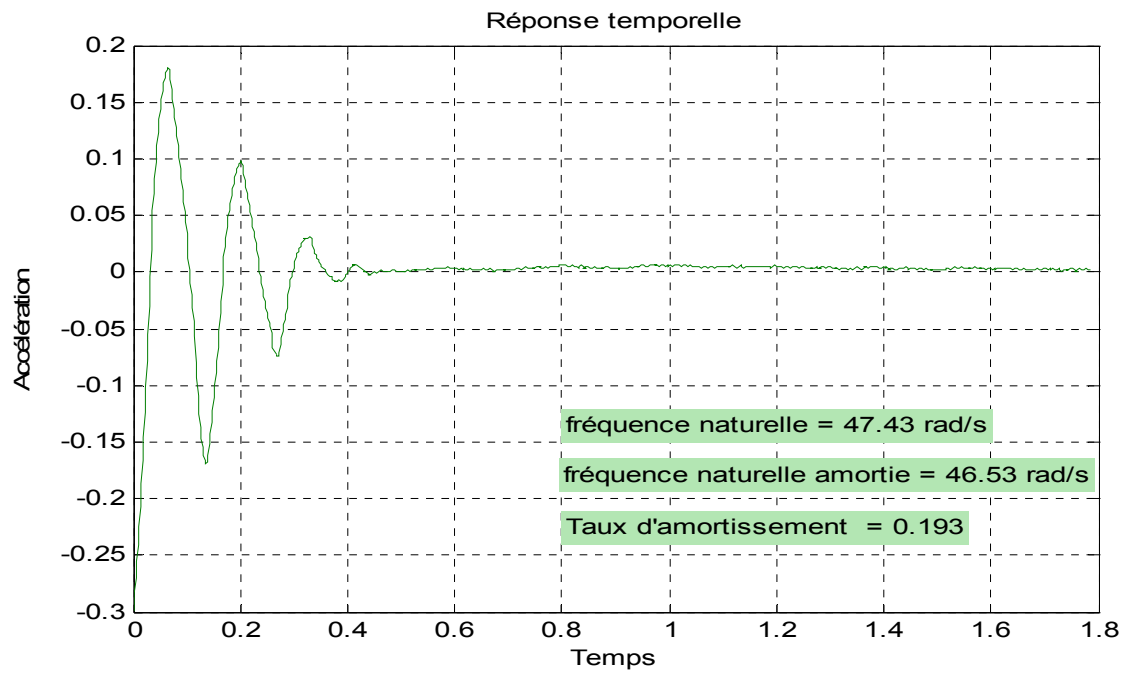
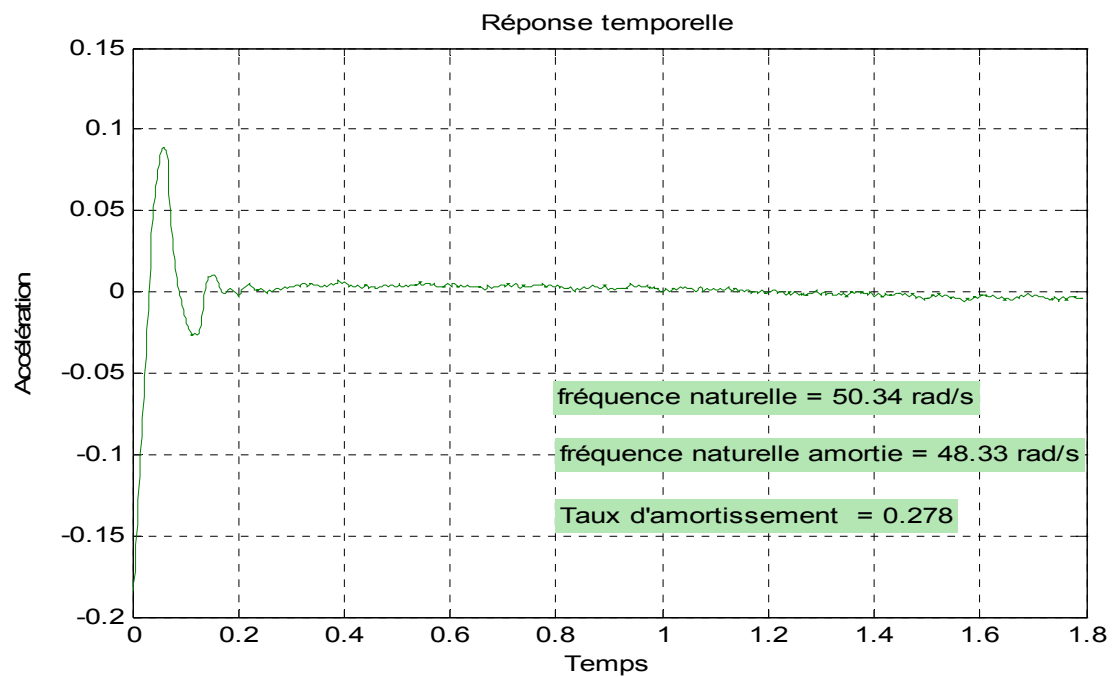
L'amortissement du fluide ER est mesuré pour des fluides ETSEF20-28, développés par nos soins [13]. Une excitation par impact a été appliquée en torsion et on a mesuré les réponses transitoires. Les valeurs des fréquences naturelles et des taux d'amortissement pour 3 champs électriques (0, 1 et 2 kV/mm) ainsi que pour le système mécanique sans fluide, sont montrés à la figure 6.

On peut constater avec surprise dans la figure 6 que la fréquence naturelle augmente avec le champ électrique. Ceci provient de l'effet du champ électrique sur la rigidité du système. On avait trouvé des résultats semblables dans une précédente étude [10]. Pour estimer la valeur de la rigidité du fluide, nous avons considéré le système comme étant à un seul degré de liberté. La figure 6-a montre que la pulsation naturelle du système sans fluide est de 42.7 rad/s.



a). Système seul sans fluide

b). Système avec fluide $E=0\text{kV/mm}$

c). Système avec fluide $E=1\text{kV/mm}$ d). Système avec fluide $E=2\text{kV/mm}$ **Figure 6 Mesure des amortissements du fluide ER en fonction du champ électrique**

Ainsi l'inertie de rotation du système mécanique peut être calculée à :

$$J = \frac{7.73}{42.7^2} = 0.00424 \quad (\text{kg} \cdot \text{m}^2) \quad (5)$$

La rigidité du système comprenant la rigidité de la structure et celle du fluide peut s'exprimer comme :

$$\begin{aligned} 0.00424\omega_n^2(E) &= k_p + k_f \\ k_f &= 0.00424\omega_n^2(E) - k_p \end{aligned} \quad (6)$$

Le tableau 2 montre l'évolution des fréquences naturelles, des taux d'amortissement et de la rigidité procurés par le fluide ER en fonction du champ électrique qui varie de 0 à 4 kV/mm.

E (kV/mm)	ω_n (Hz)	k_f (N.m/rad)	ζ
Structure seule	42.7	0	0.048
0	45.39	0.92	0.055
1	47.43	1.72	0.193
2	50.34	2.91	0.278
3	57.78	6.29	0.381
4	60.01	7.40	0.404

La figure 7 montre que la rigidité de torsion k_f du fluide ER croît rapidement avec le champ électrique.

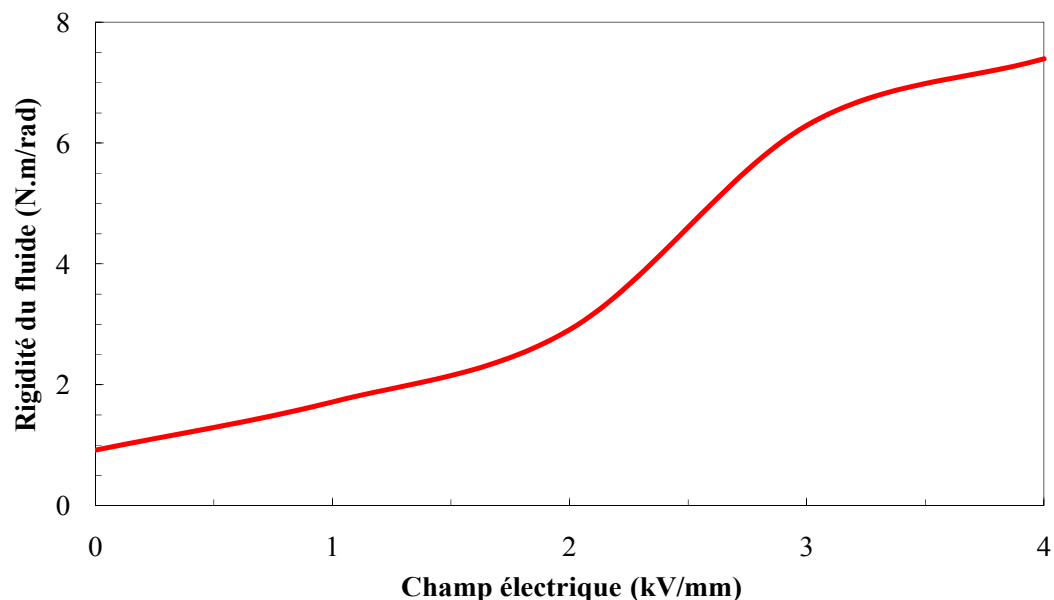


Figure 7 Variation de la rigidité du fluide en fonction du champ électrique

Nous pouvons constater que la rigidité de torsion du fluide varie de 0.92 à 7.40 N.m/rad, ce qui donne un accroissement de l'ordre de 700%. On peut constater également une augmentation importante de la rigidité pour des champs électriques variant entre 2 et 3 kV/mm.

Tel qu'attendu, ces résultats (tableau 2) nous montrent que l'amortissement du fluide ER croît avec le champ électrique. La variation du taux d'amortissement est montrée à la figure 8. Les taux d'amortissement varient de 5.5 % à 40.4 %, ce qui représente un accroissement de l'ordre de 600 %. On peut constater que l'amortissement croît pratiquement linéairement pour des champs électriques inférieurs à 3 kV/mm, après quoi on peut remarquer un accroissement asymptotique, ce qui montre sa limite.

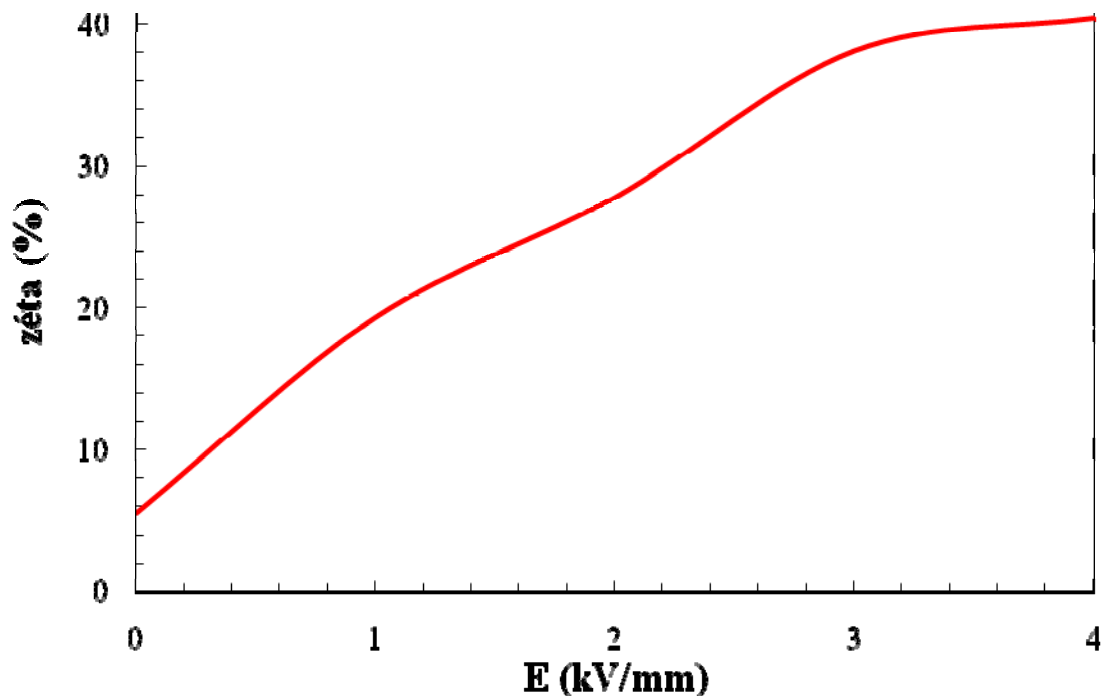


Figure 8 Variation du taux d'amortissement en fonction du champ électrique.

6.0 CONTRÔLE DES VIBRATIONS DE TORSION DU ROTOR

6.1 Modélisation d'un amortisseur ER cylindrique rotatif

Le système a été modélisé comme un système à 1 ddl de torsion (figure 9). Il comprend une inertie de rotation J , un élément de friction (coulomb), un élément de rigidité k_{sys} du système qui comprend la rigidité de la poutre et celle du fluide et un élément d'amortisseur visqueux non-linéaire de torsion qui contient le fluide ER dont les propriétés sont définies selon le modèle de quasi-Bingham (eq. 4).

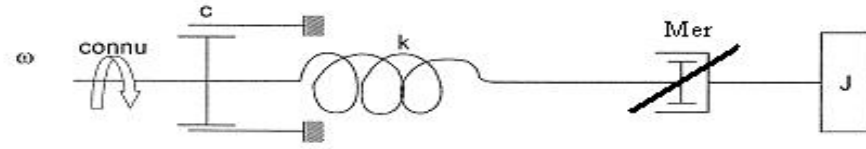


Figure 9. Modèle mécanique de contrôle semi-actif par fluide ER

L'équation de mouvement de système est :

$$J\ddot{\theta} + C(\dot{\theta} - \dot{\theta}_0) + K_{sys}(\theta - \theta_0) = -M_{ER} \quad (7)$$

où M_{ER} est le couple généré par le champ électrique;

C est le coefficient d'amortissement qui produit de fluide ER quand le champ électrique n'est pas appliqué et qui n'est pas contrôlable. Il peut être considéré comme un amortissement passif pour garder le système robuste.

$$C = \frac{2\pi R^3 H (\eta_\infty)}{R - R_0} \quad (8)$$

Les paramètres d'amortissement peuvent être obtenus en fonction de la géométrie de système dans lequel R est le rayon du cylindre extérieur, R_0 est le rayon du cylindre intérieur J et H est la hauteur du cylindre intérieur. Le couple M_{ER} du au fluide ER est composé d'un couple de friction M_{cf} et d'un couple visqueux qui dépend du champ électrique. On a :

$$M_{ER} = M_{cf} + C_{ER}(\dot{\theta} - \dot{\theta}_0) \quad (9)$$

où M_{cf} est le couple de friction, C_{ER} est le coefficient d'amortissement non-linéaire en torsion.

Le couple de friction dépend du seuil d'écoulement. On a :

$$M_{cf} = 2\pi R^2 H \tau_c \operatorname{sgn}(\dot{\theta} - \dot{\theta}_0) = \begin{cases} 2\pi R^2 H \tau_c & \text{Si } (\dot{\theta} - \dot{\theta}_0) > 0 \\ 0 & \text{Si } (\dot{\theta} - \dot{\theta}_0) = 0 \\ -2\pi R^2 H \tau_c & \text{Si } (\dot{\theta} - \dot{\theta}_0) < 0 \end{cases} \quad (10)$$

En appliquant l'équation 4, on obtient le coefficient d'amortissement visqueux :

$$C_{ER} = \frac{2\pi R^3 H(\eta_0 - \eta_\infty)}{(R - R_0) \left[1 + \left(\frac{tR(\dot{\theta} - \dot{\theta}_0)}{(R - R_0)} \right)^n \right]} = C'_{ER} \frac{1}{1 + \left(\frac{tR(\dot{\theta} - \dot{\theta}_0)}{(R - R_0)} \right)^n} \quad (11)$$

$$\text{où } C'_{ER} = \frac{2\pi R^3 H(\eta_0 - \eta_\infty)}{R - R_0} \quad (12)$$

Dans cet article, nous avons considéré un contrôle en boucle ouverte pour réaliser le contrôle semi-actif. Le principe de contrôle consiste à obtenir une transmissibilité optimale. Quand le système est soumis un couple d'excitation, l'équation de mouvement du système est la suivante :

$$J\ddot{\theta} + C(\dot{\theta} - \dot{\theta}_0) + K(\theta - \theta_0) + M_{ER} = M \quad (13)$$

Pour avoir une minimum transmissibilité, il faut augmenter l'amortissement du système quand la fréquence d'excitation est proche de la fréquence naturelle du système (le champ électrique est mis à 'ON' pour avoir M_{ER} maximum), mais il faut minimiser l'amortissement du système quand la fréquence d'excitation est supérieur 1.414 fois de la fréquence naturelle (le champ électrique est alors mis à 'OFF' pour avoir M_{ER} nul).

6.2 Simulations de l'amortisseur ER avec Simulink

Une modélisation numérique à l'aide de Simulink a été appliquée en utilisant le modèle de quasi-Bingham (eq 4). L'amortissement C du fluide lorsque le champ électrique n'est pas activé a été calculé à 0.00924 (eq 8). Le couple de friction a été estimé à 0.0365 N.m (eq 10). Le coefficient C'_{ER} de l'équation (12) a été calculé à 0.0307 en considérant un champ électrique de 2 kV/mm. La figure 10 présente le modèle Simulink.

La figure 11 présente les résultats de transmissibilité des déplacements angulaires du système sous excitation harmonique en fonction du rapport des fréquences. La figure 11-a présente la transmissibilité quand un amortissement passif est appliqué, la courbe en bleu représente le cas lorsque le champ électrique n'est pas appliqué et la courbe en rose présente le cas où un champ électrique de 2kV/mm est appliqué en permanence.

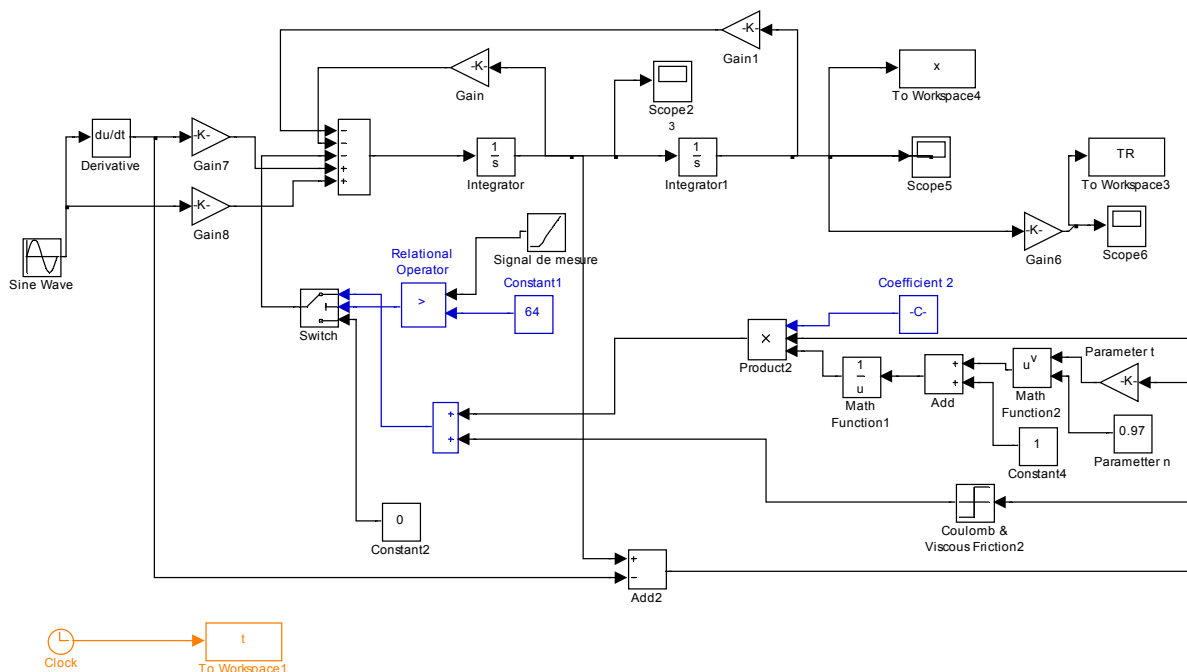


Figure 10 Modèle Simulink du contrôle des vibrations de torsion

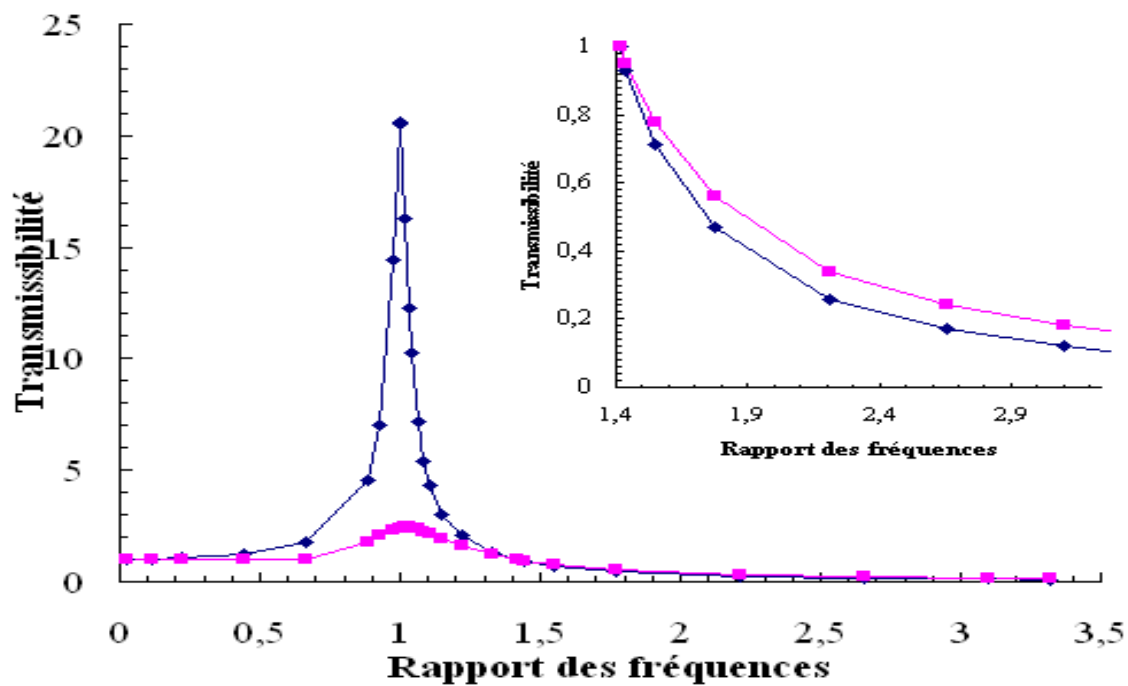


Figure 11 Amortissement passif avec et sans champ électrique

La figure 12 présente le résultat du contrôle semi-actif en appliquant la loi de contrôle qui consiste à appliquer le champ électrique quand la fréquence d'excitation est inférieure à 1.4 fois de la fréquence naturelle et à l'enlever lorsqu'elle est supérieure.

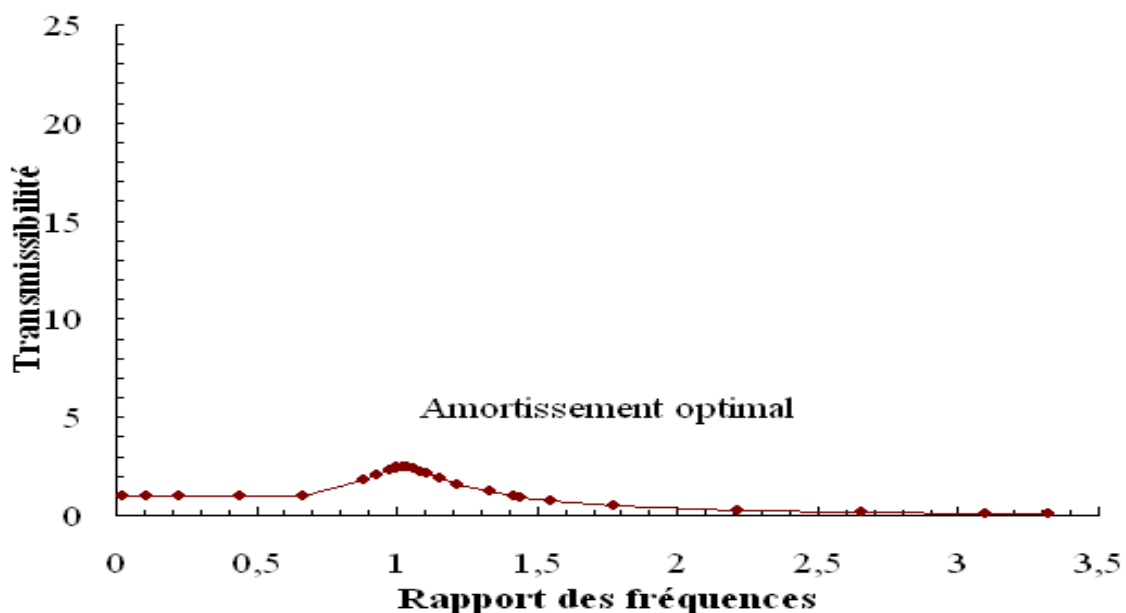


Figure 12 Résultats du contrôle semi-actif

7.0 CONCLUSION

Dans cet article, un nouveau modèle appelé Quasi-Bingham est présenté pour mieux décrire le comportement rhéologique des fluides ER. Ce modèle s'est avéré bien représentatif des essais expérimentaux pour prédire le rhéogramme. En appliquant ce nouveau modèle, nous avons développé un nouveau modèle d'amortisseur qui contient trois éléments, soit : un élément de rigidité, un élément dissipatif de friction et un élément visqueux non-linéaire. Ce modèle d'amortisseur ER a été appliqué à un système simplifié à un degré de liberté. Toutefois, ce modèle nous a permis de réaliser numériquement un système de contrôle semi-actif des vibrations en torsion de rotors. La simulation a été faite par Simulink. Les travaux futurs auront pour but de réaliser un prototype d'amortisseur ER pour vérifier le modèle et élaborer une stratégie de contrôle plus sophistiquée.

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9. REMERCIEMENTS

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10. BIOGRAPHIES

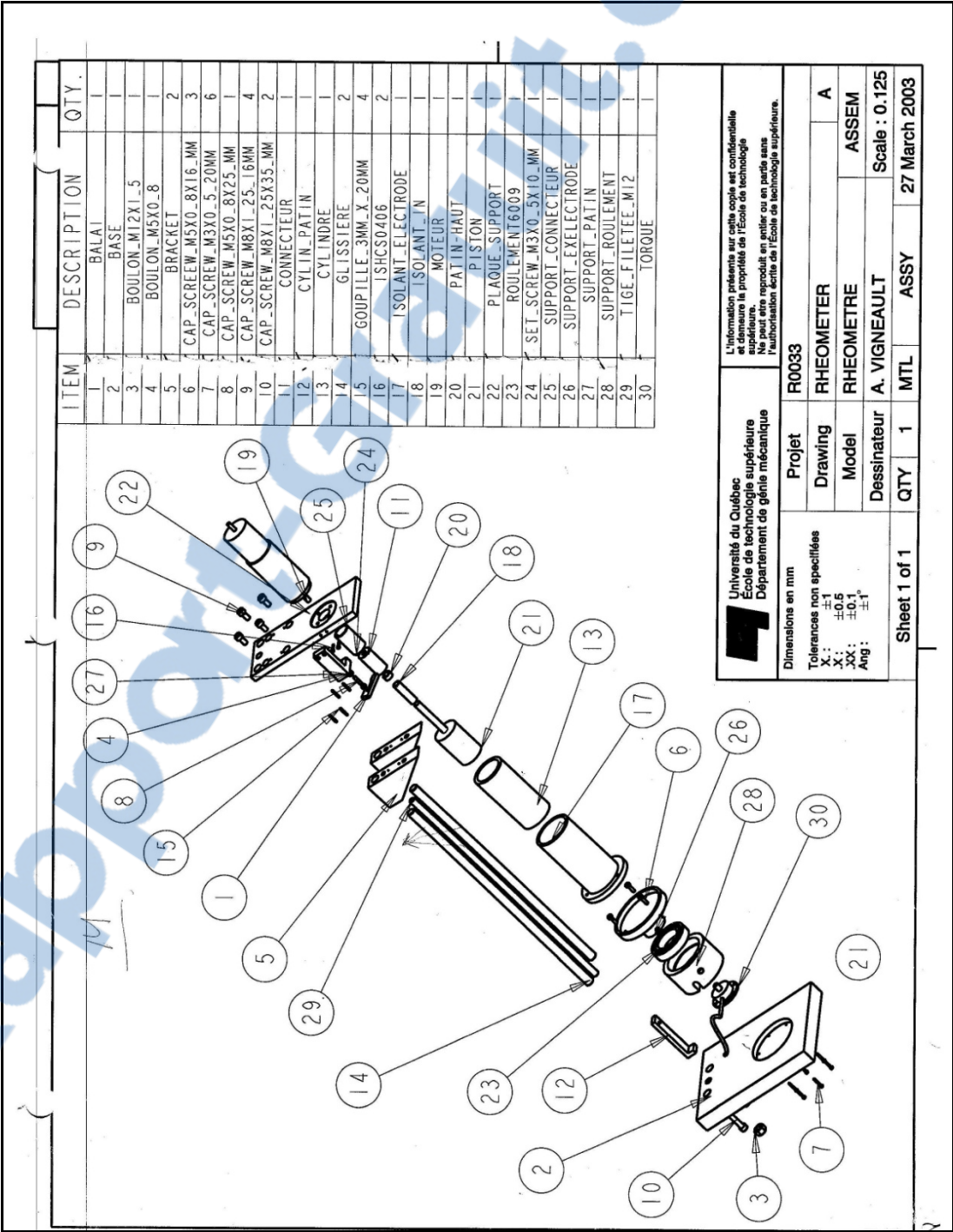
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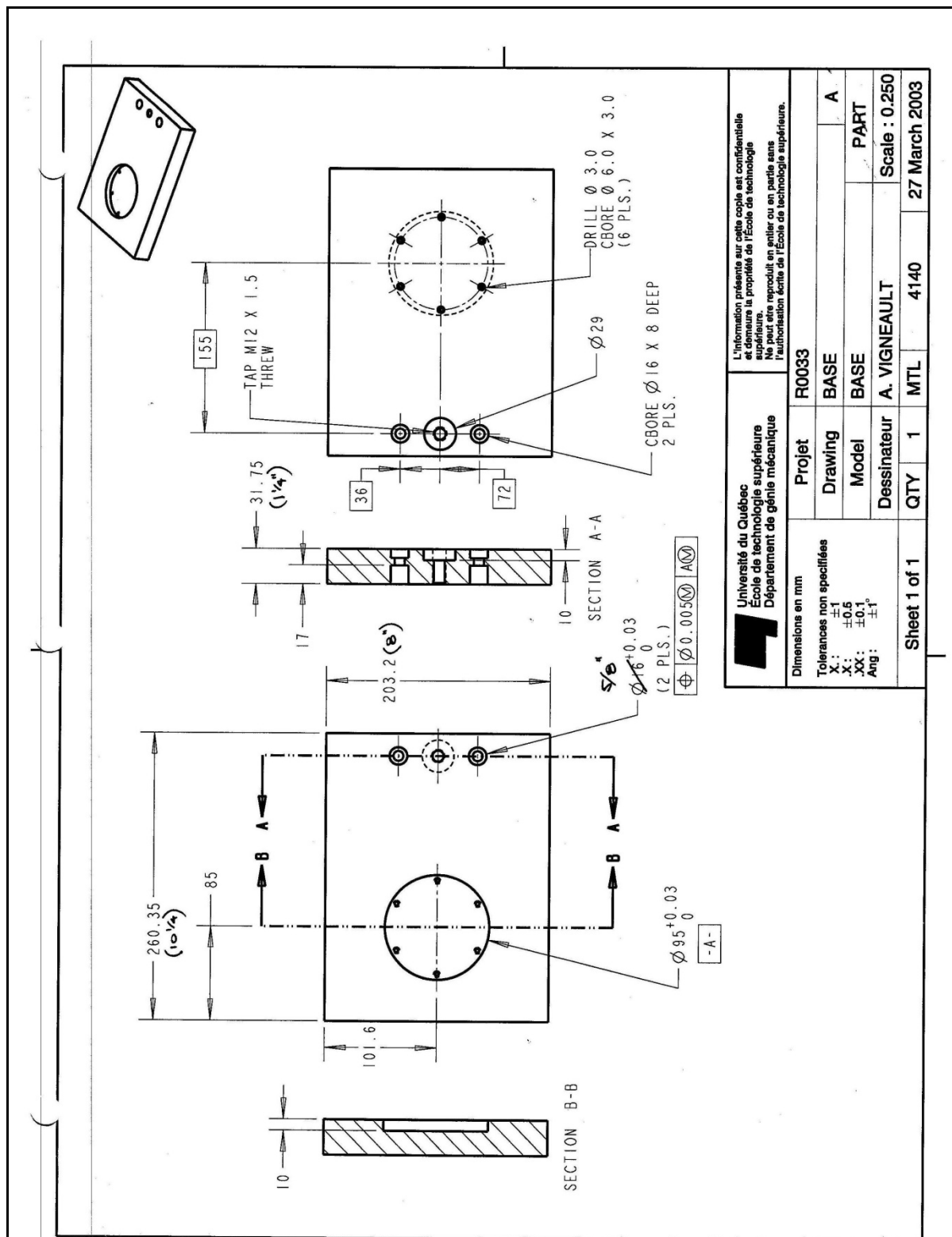
Marc Thomas est un professeur en génie mécanique de l'école de technologie supérieure (Montréal), spécialisé en maintenance, fiabilité et vibrations. Il est mentor du chapitre Québec de l'association canadienne en vibration de machines (ACVM). Il est le directeur de thèse de Yulan Sun.

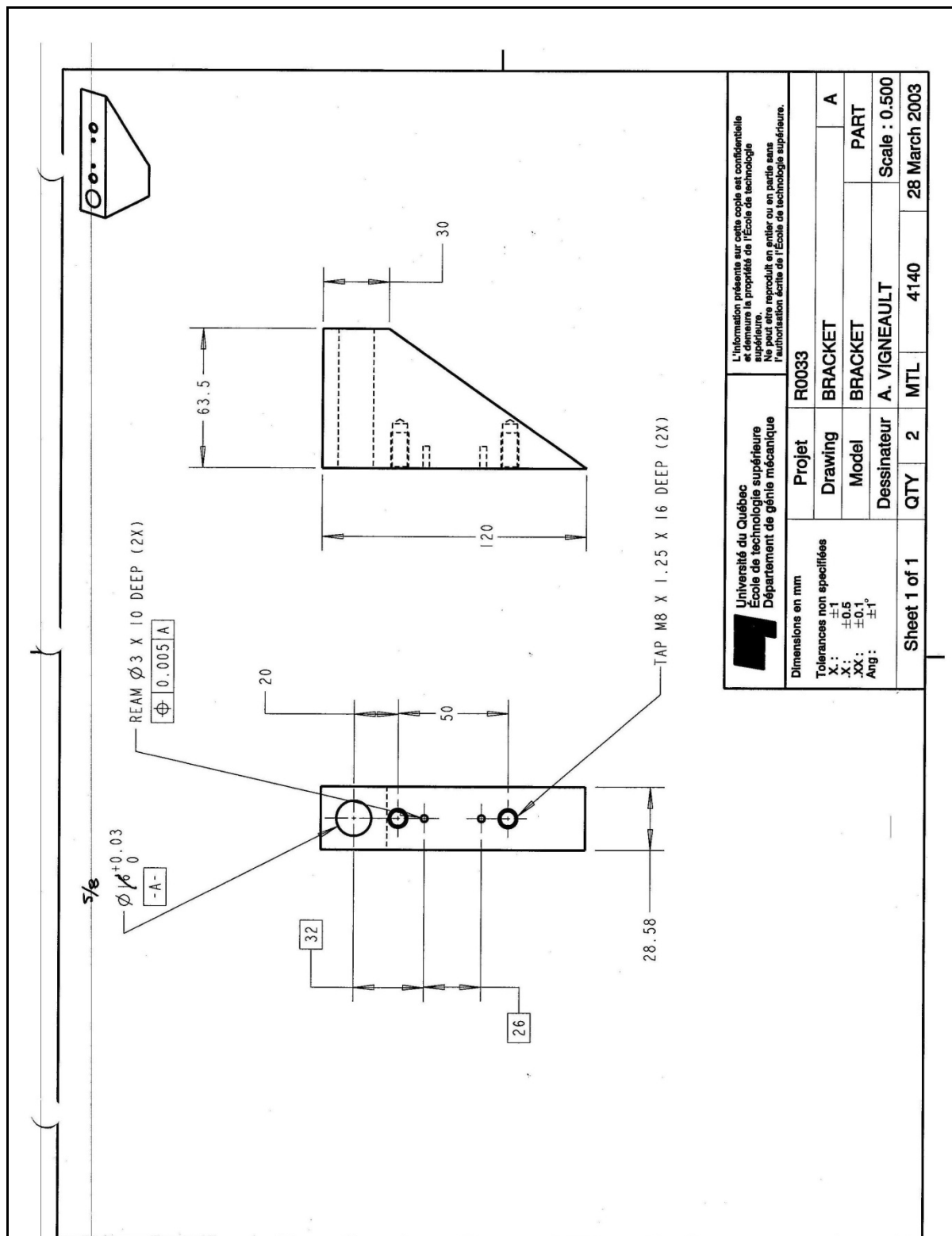
Jacques Masounave est un professeur en génie mécanique à l'école de technologie supérieure (Montréal). Ses activités de recherche sont orientées vers les matériaux, les techniques de mise en forme et l'usinage propre. Il est le co-directeur de thèse de Yulan Sun.

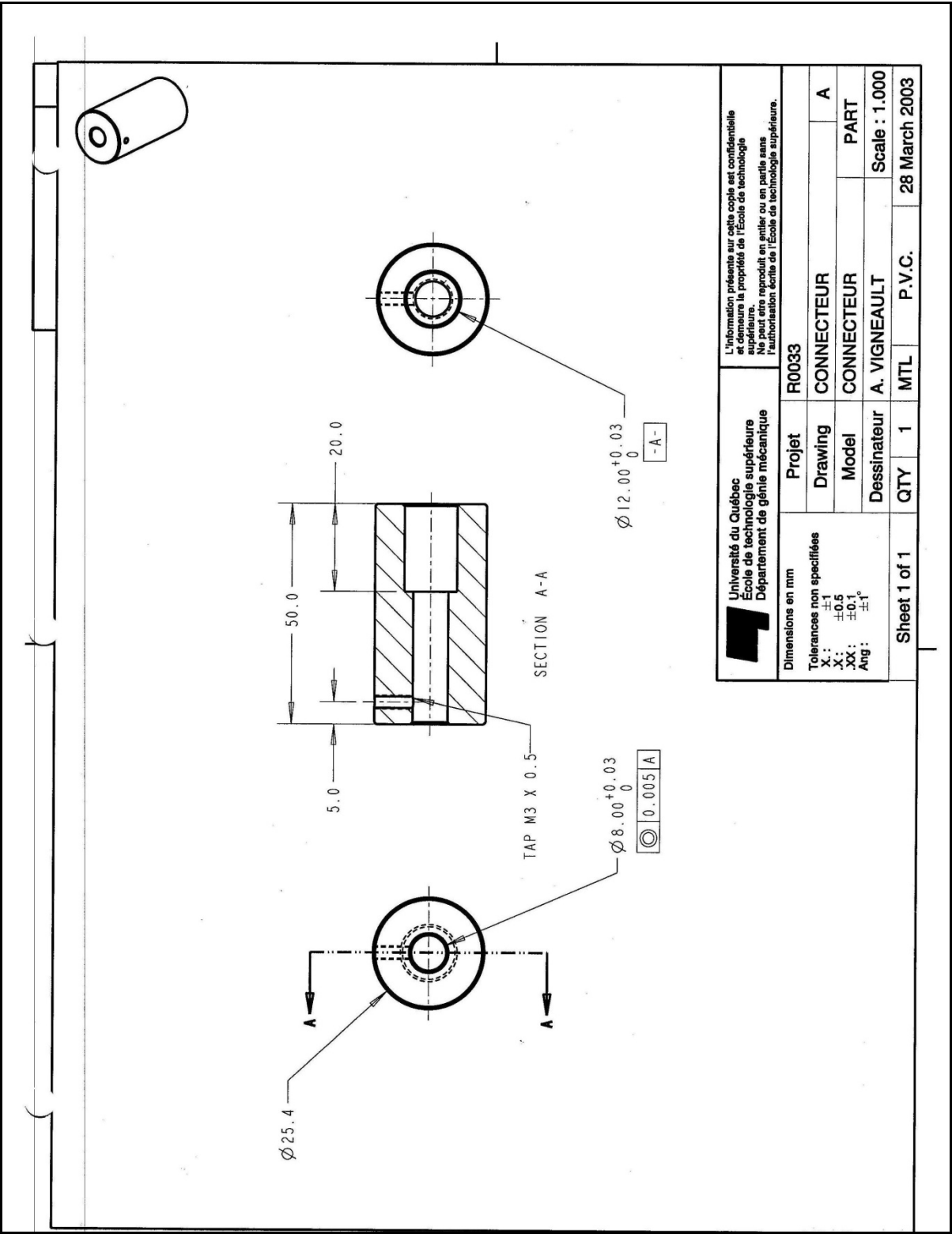
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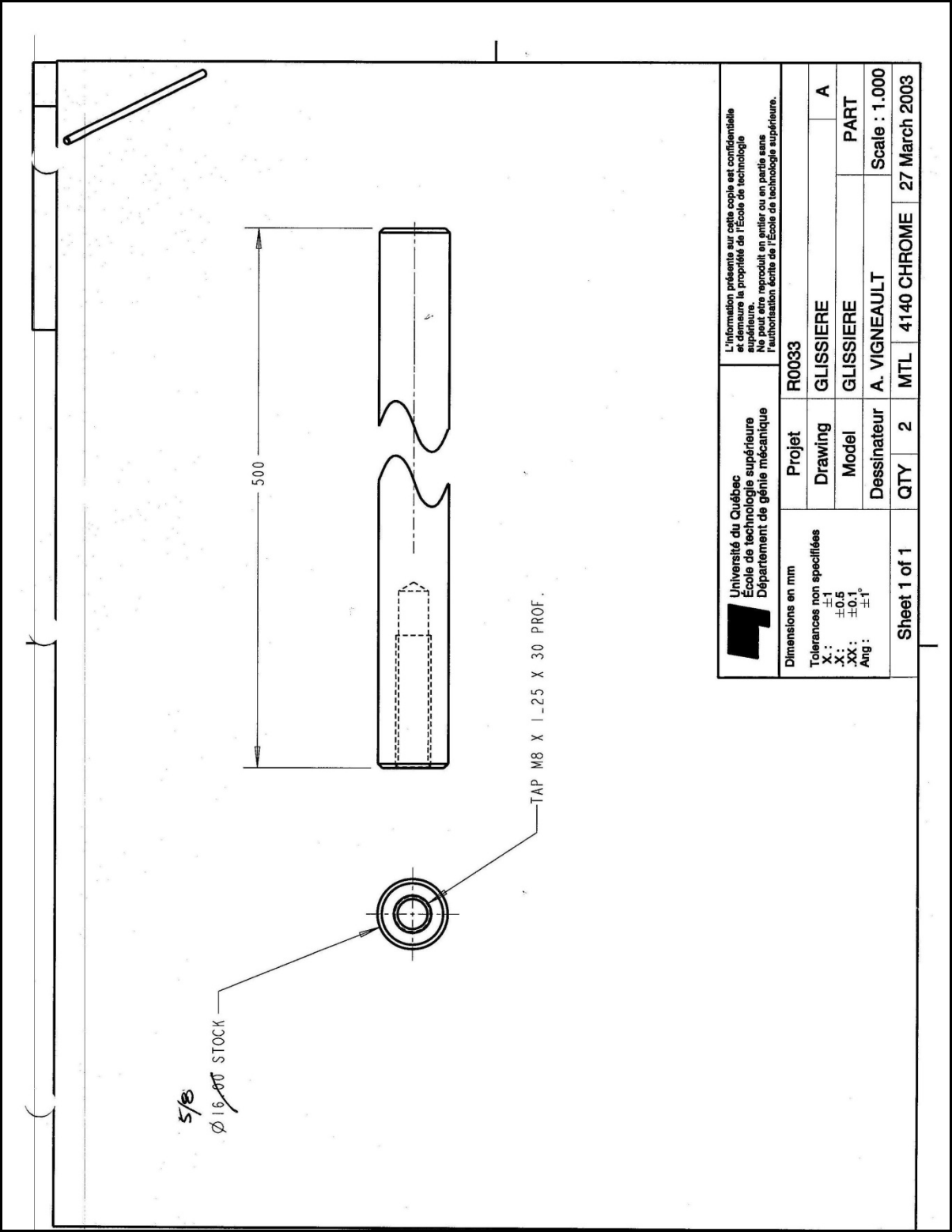
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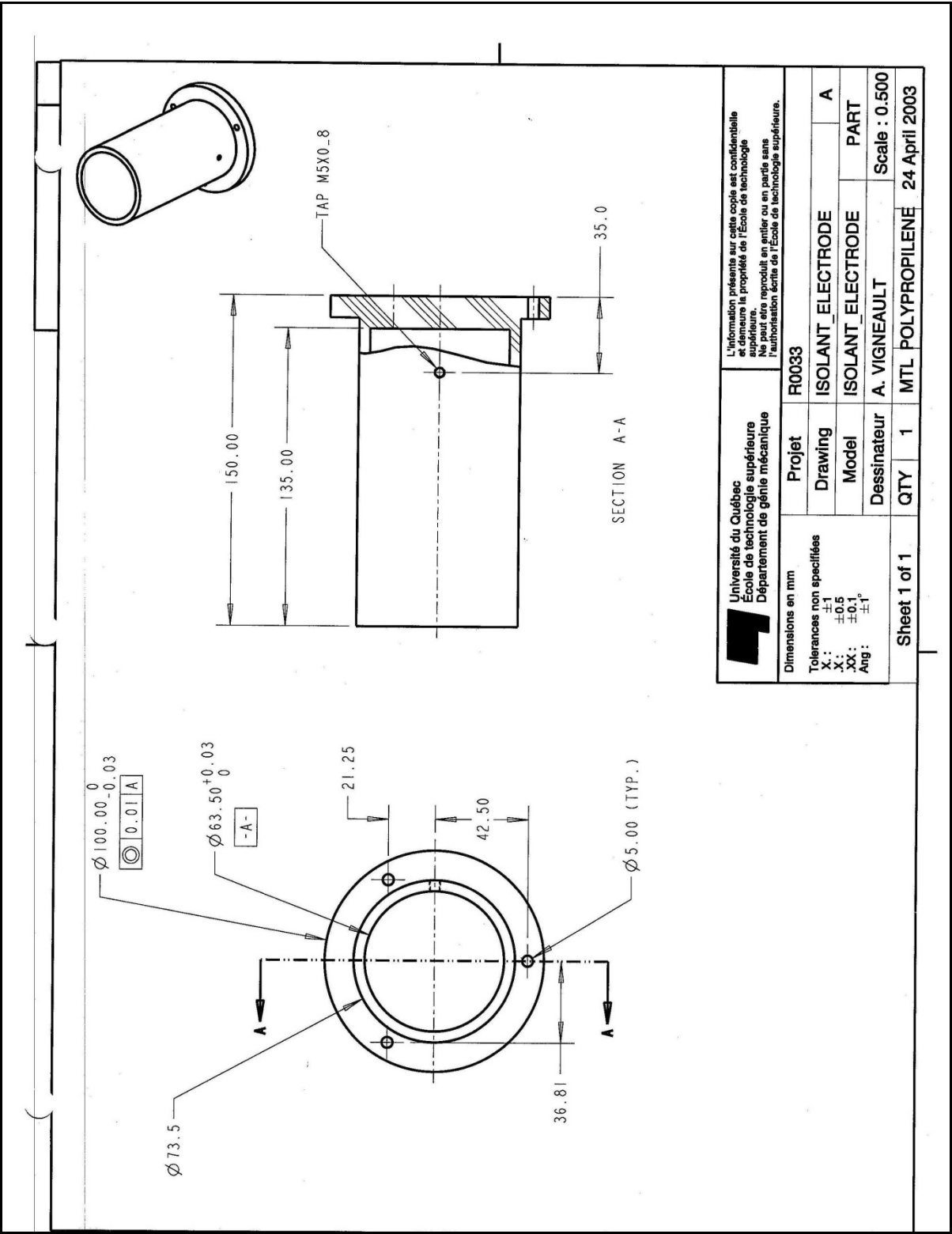


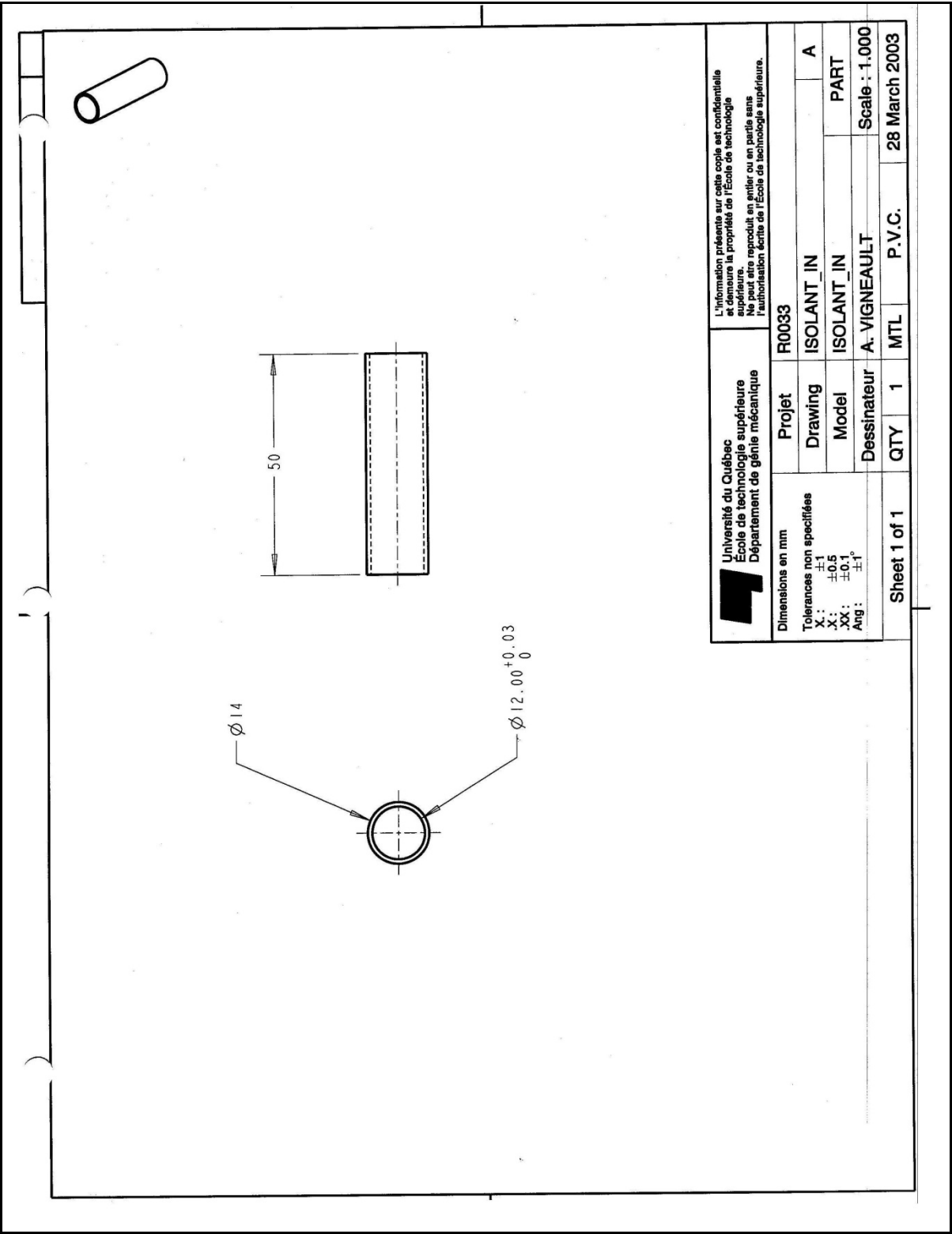


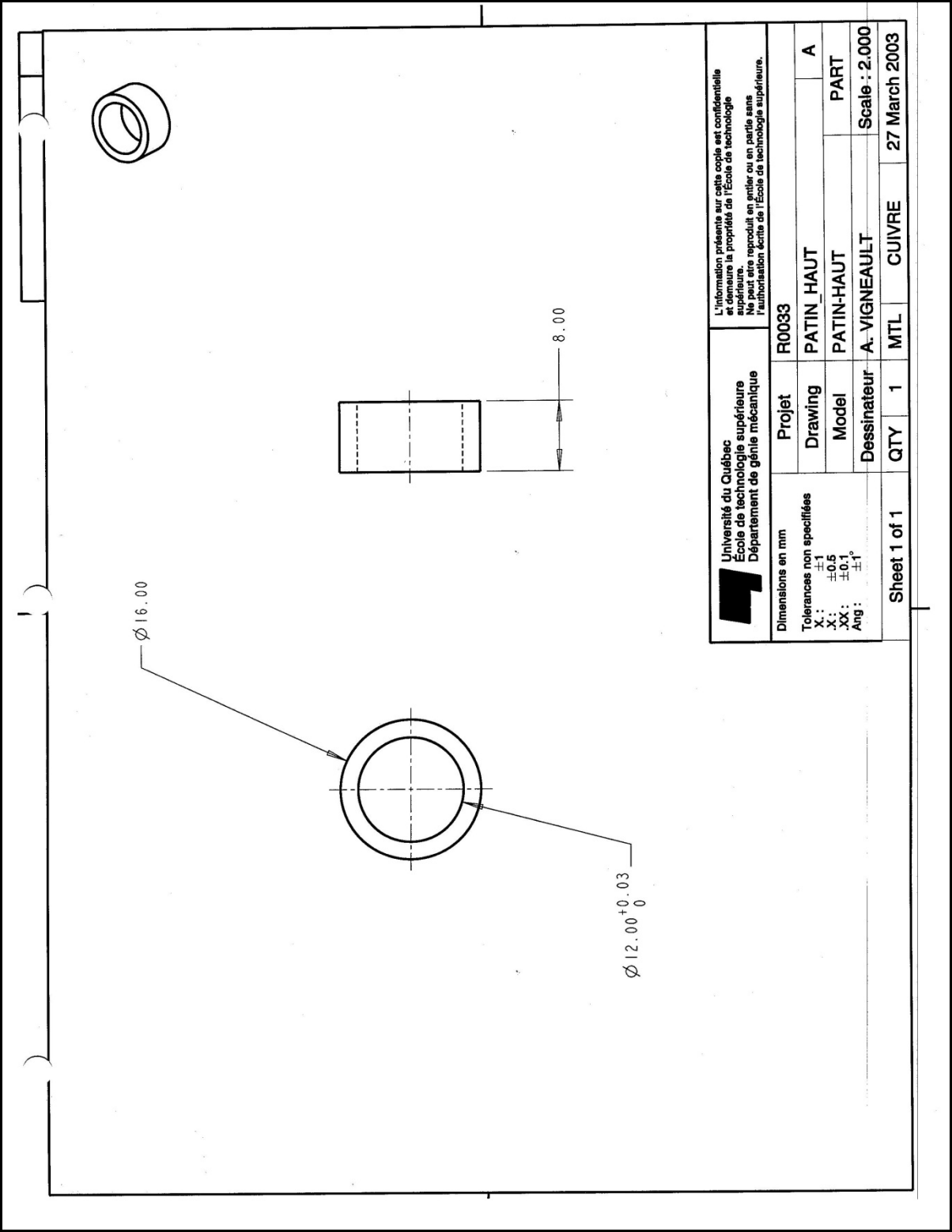


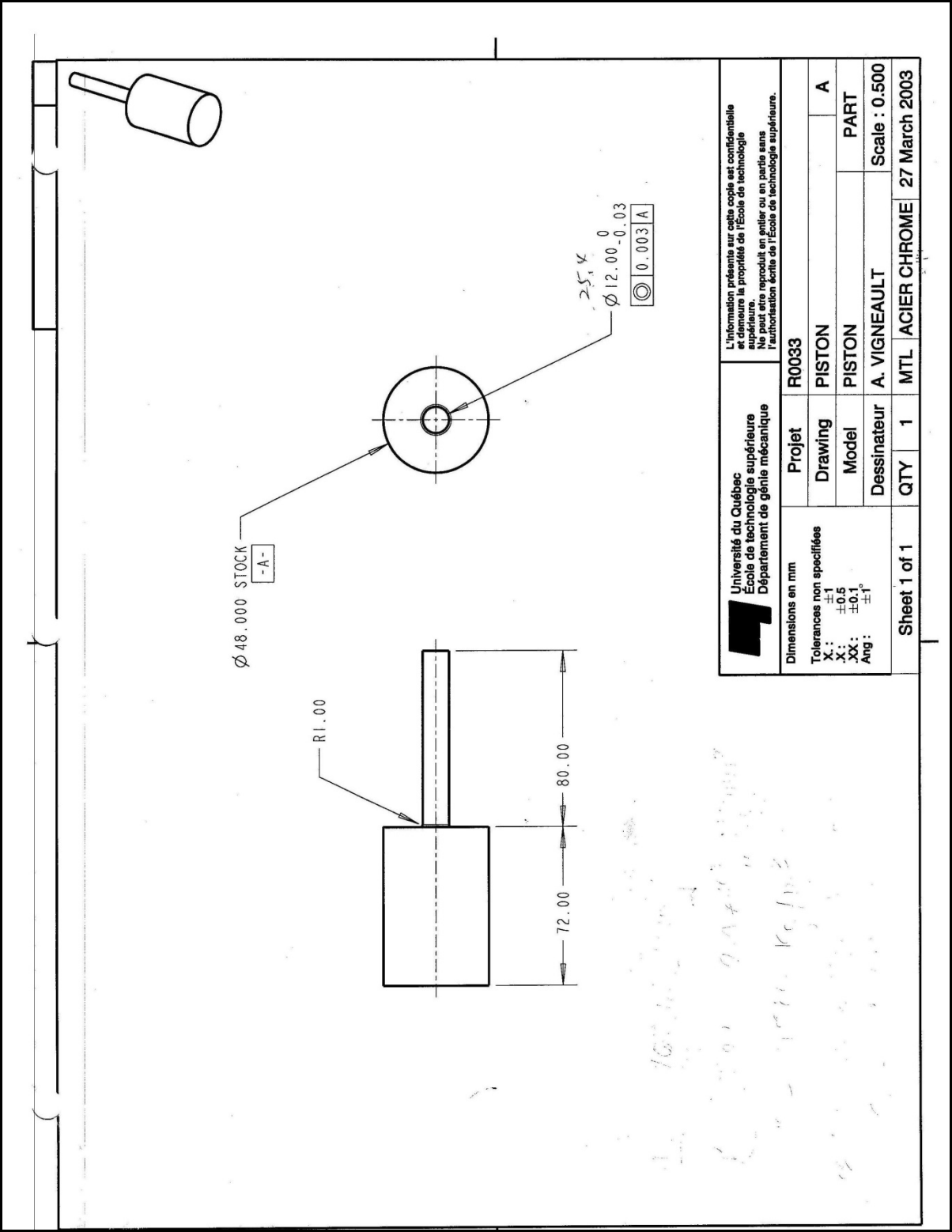


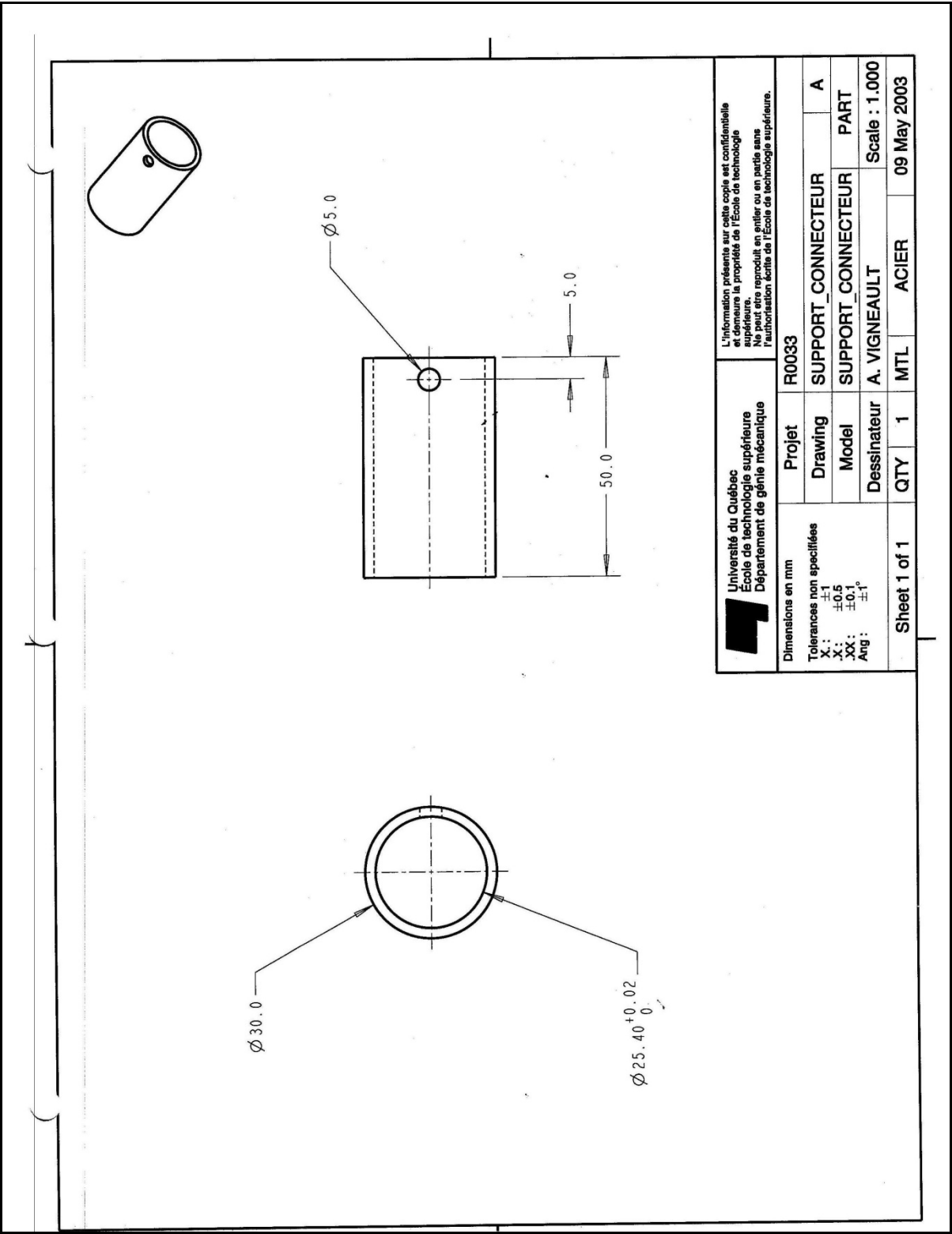


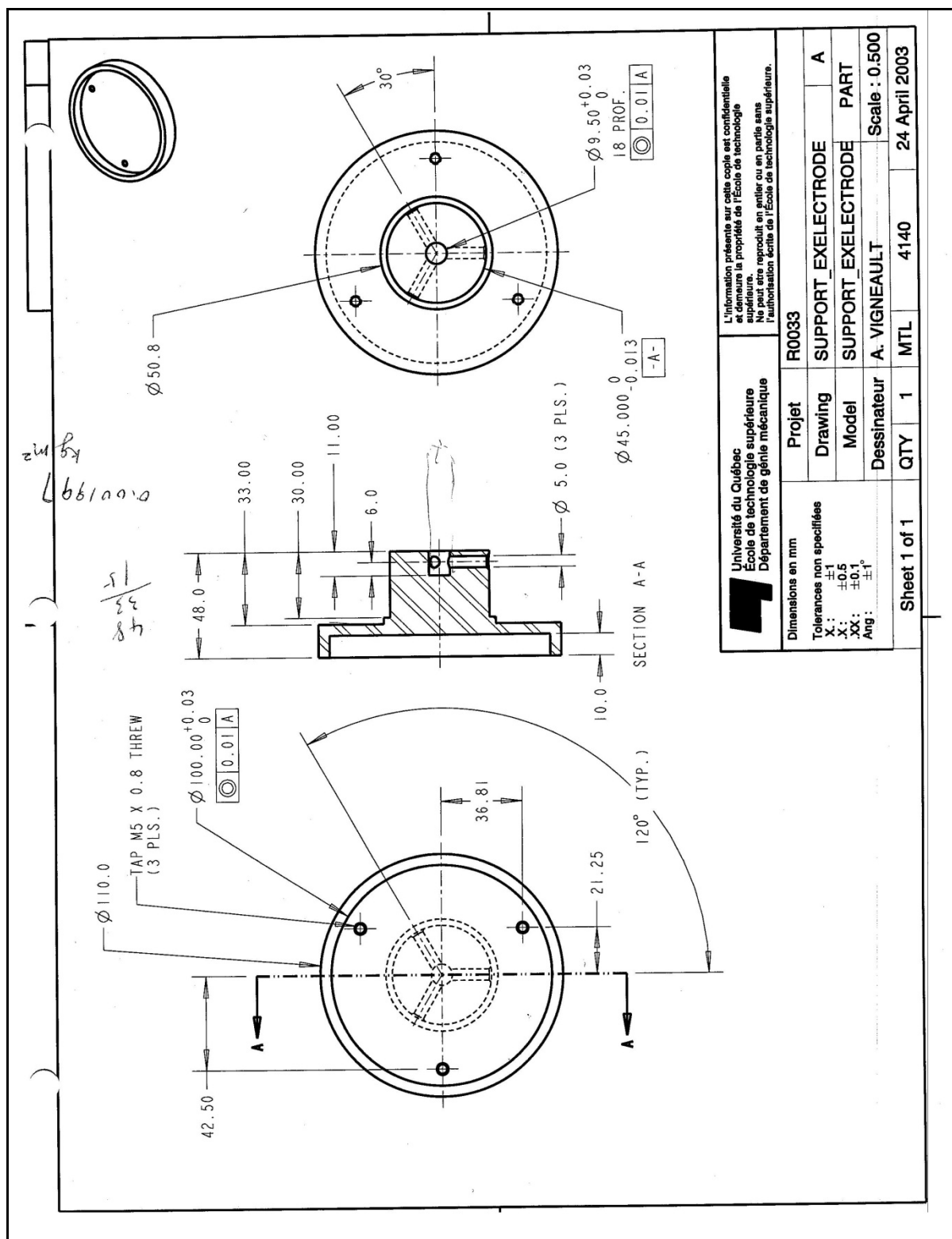


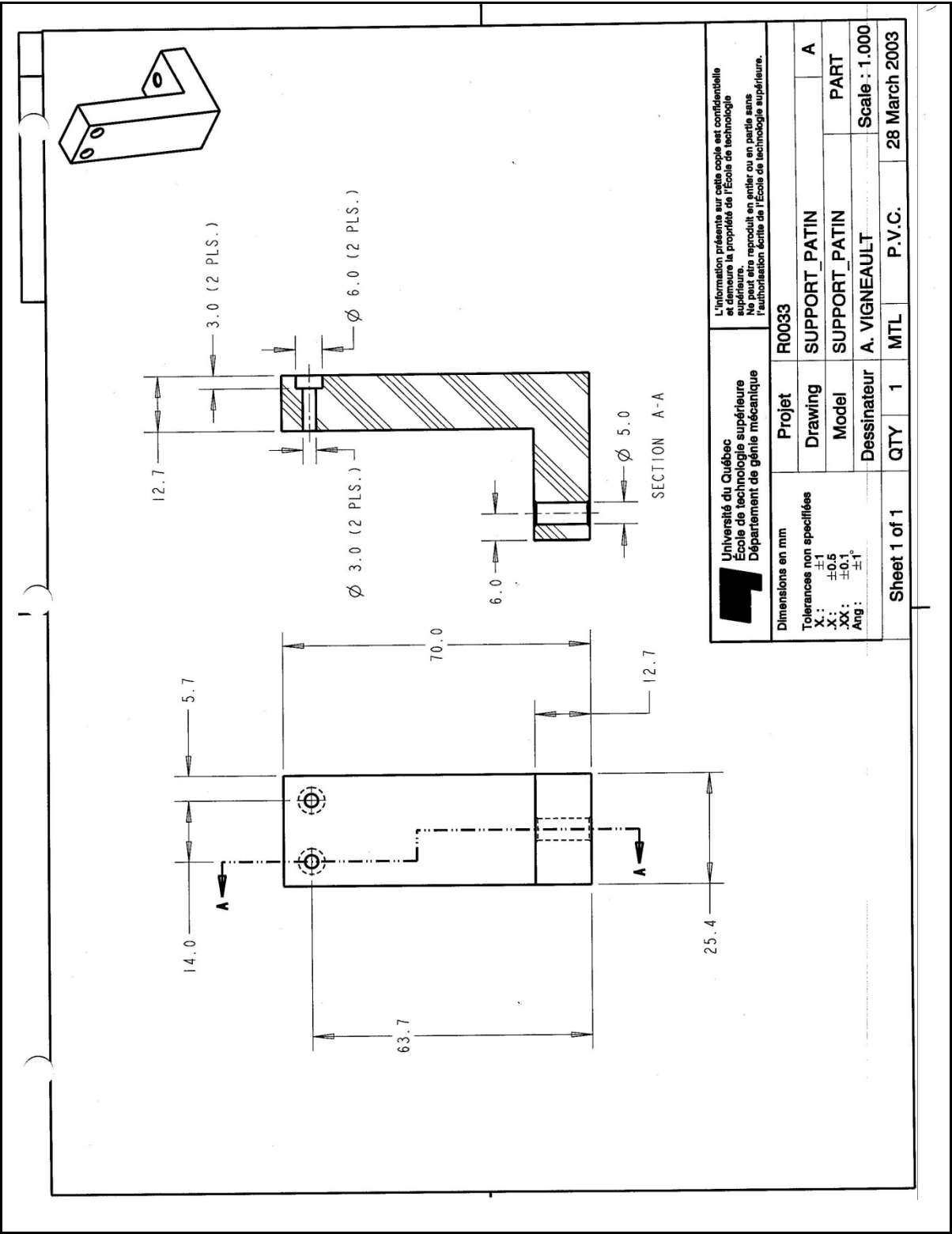


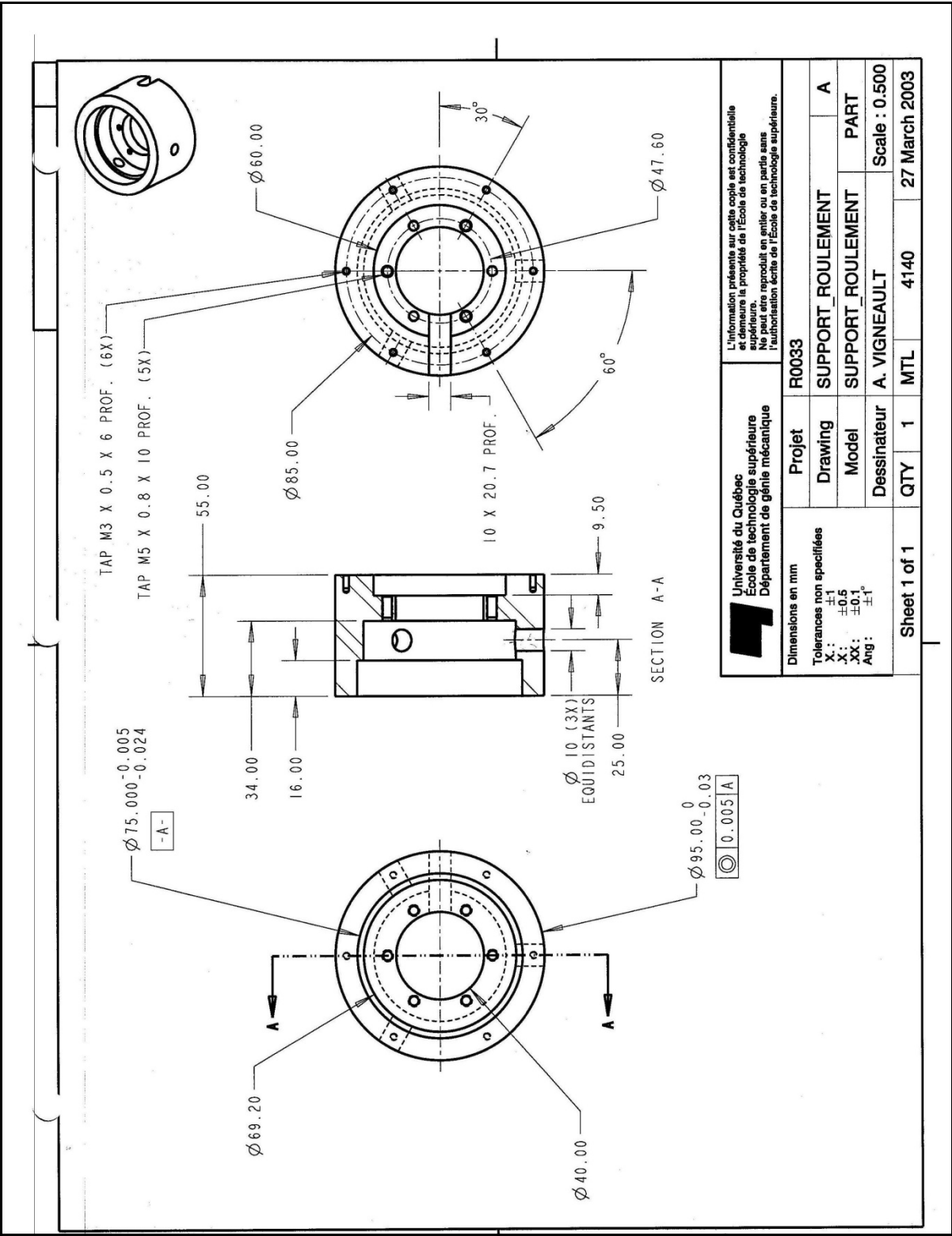


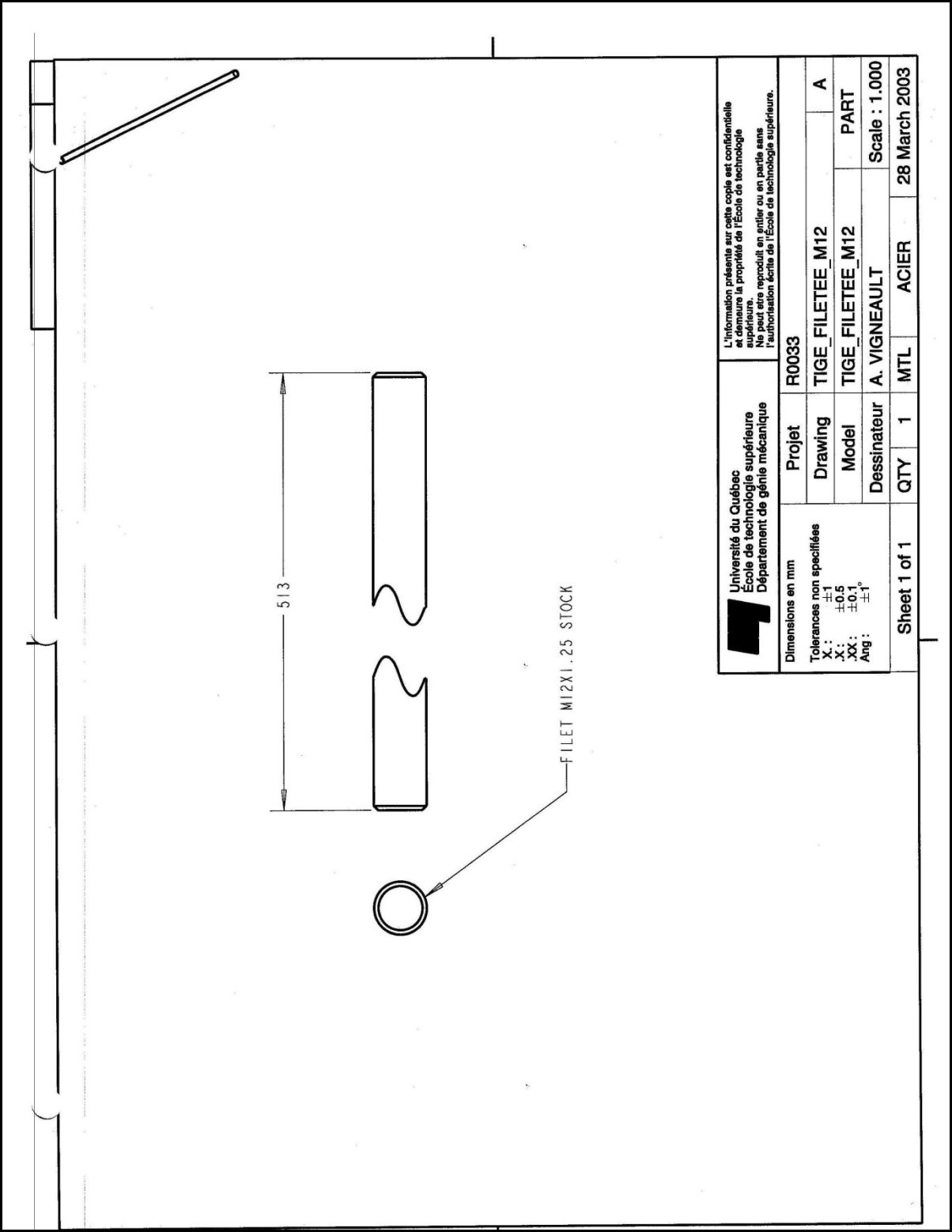




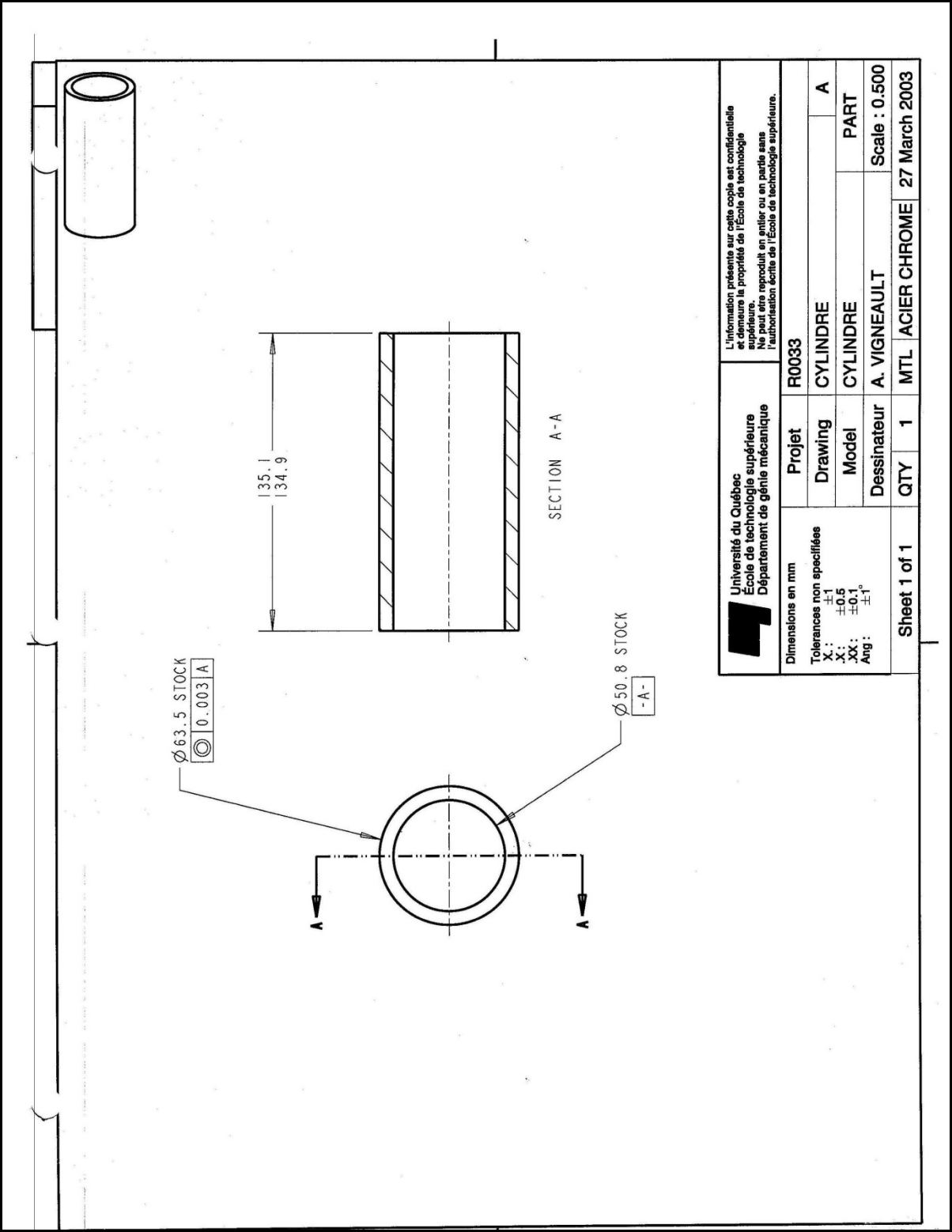








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