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CONTROL OF RADIATION HEAT TRANSFER THROUGH A COMPOSITE WINDOW FEATURING ER FLUID: A CONCEPTUAL INVESTIGATION*

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Radiation heat transfer control through the application of an electric field upon an Electrorheological (ER) fluid based composite material is an innovative new area of research. A conceptual experiment has been conducted to study radiation heat transfer through a composite window featuring an ER fluid. The composite window is composed of two thin glass plates with a layer of ER fluid contained between them. The glass walls were transparent except for a very thin coating of an electric-conductive film which enabled the inside of the glass surfaces to serve as electrodes. The ER fluid was contained between the glass surfaces and consisted of a suspension of micron sized crystalline zeolite particles in a silicon oil. This study has demonstrated the unique capability of ER fluids to regulate and control radiation heat transfer via transmittance measurements. A semi-empirical model is developed from the experimental data to correlate the dependence of radiation transmission through ER fluids based on several physical parameters (f_V, V^*, and L). This model agrees reasonably well with the measured data. The results obtained in this study are very important to those concerned with the development of a thermally smart material for heat transfer control.

INTRODUCTION

The stringent controls and demands of technologically-advanced industry have created a need for the thermally smart structure: a system or material which has built-in intrinsic sensors, actuators and control mechanisms. For this purpose high performance, compact and self-contained heat transfer control units are especially desirable. Recent studies have shown the potential capabilities of Electrorheological (ER) fluid in heat transfer control (Shul'man, 1982; Zhang and Lloyd, 1992).

ER fluids are suspensions of highly polarizable micron sized particles suspended in suitable carrier fluids. When an electric field of sufficient strength is applied (i.e., 1-3 kV/min), they give rise to a complex fibrous structure, electrically induced fibration (Winslow, 1947), composed of tightly formed particle-chains generally aligned with the applied electric field. The immediately obvious effect is that the viscosity of the fluid is increased, possibly even forming an elastic-plastic substance if the particle concentrations are high enough. This process is reversible. Upon removal of the field, these particle aggregates break up as the thermally induced motion overcomes the weak colloidal forces that hold them together. Such a unique feature of ER fluids suggests that it may be exploited to enable the control of heat and mass transfer.

For example, radiation through a composite window filled with ER fluid (see Fig. 1) should be controllable. ER fluids without an applied field can be treated as an absorbing, emitting and scattering medium. The process of radiative heat transfer through this type of medium has been the subject of considerable number of studies in heat transfer as reviewed by Buckius (1986). Upon application of an electric field, the entire particulate suspension transforms into a system of particle chains. Radiation is then transferred through a medium containing numerous cylindrical fibers which are controlled by the applied electric field. The interactions between electric field, particle

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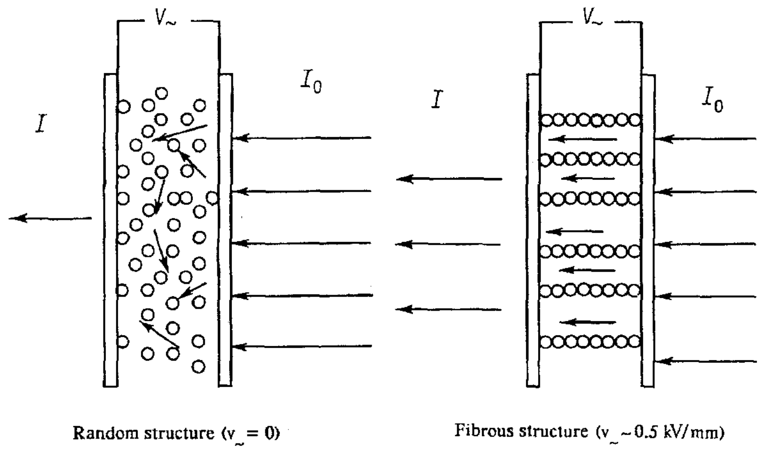

Fig. 1. Conceptual schematic of ER fluid.

movement and temperature creates a new control mechanism for radiant energy transfer. Thus, it is of primary importance to explore the use of this physical effect of electrically-induced fibration for the development of a new type of heat transfer control system.

Electrorheology is an interdisciplinary field. During its relatively short research history (less than 40 years) there has been very few studies concerning ER phenomena in heat transfer application. The fundamental mechanism has yet to be clarified. A recent numerical study by Klingenberg et al. (Klingenberg, Frank van Swol and Zukoski, 1989) shed light on the dynamic fibration process in which they suggested the particle motion at short times is characterized by the formation of small clusters, and at long times by the interactions between large and percolating clusters. Most of the previous applications of ER fluids have been primarily focused on flow control (Arguelles et al., 1973), power transmission and shock and vibration attenuation (Bullough et al., 1973; Duclos et al., 1987; Ushijima et al., 1988), largely because of the rheological characteristics, viscosity control by the field, of ER fluids. There was a study in Russia by Shul'man (1982) and Shul'man et al. (1986) who reported the enhancement of heat transfer in heat exchangers by utilizing ER fluids. At the same time, Cerda et al. (1981a; 1981b) studied electro-optical phenomena in fibrated suspensions, in which they qualitatively measured the transmittance through a dilute guanine and silvered erythrocyte suspension subjected to a 60-Hz electric field (strength: 15 V/mm to 50 V/mm).

The objective of this research is to address and explore an innovative concept for controlling radiation heat transfer through an ER fluid based composite window. A conceptual experiment was systematically conducted to investigate the potential capability of ER fluid in controlling radiation transfer. Also discussed here is the controlling mechanism for this peculiar phenomena in light of current findings and those theory postulated in the literature. The result of this work clearly demonstrated the unique character of ER fluids in their ability to alter and control radiation transfer, and it proposed a simple but realistic transmission model derived from experimental data and retains the essence of physical mechanism.

EXPERIMENTAL

As shown in Fig. 2, a He-Ne laser beam (polarized and with wavelength of 0.6328 μ) was directed normally at a small composite window. This rectangular composite window (38×19 mm^2) was filled with a layer of ER fluid with pathlengths varying from 0.5 mm to 2 mm. The inner surfaces of window glass were coated with a thin film of electric conductive Indium Oxide to enable them to serve as electrodes. A high voltage ($\sim$6000 V) luminous gas tube transformer was used to apply the electric field across the ER fluid. The transmitted laser beam intensity was measured using an Oriel 77344 photomultiplier tube which was mounted on a demountable optical holder. The PMT signal was processed by an Oriel 7070 PMT readout instrument and fed to a Fluke 2625A data acquisition

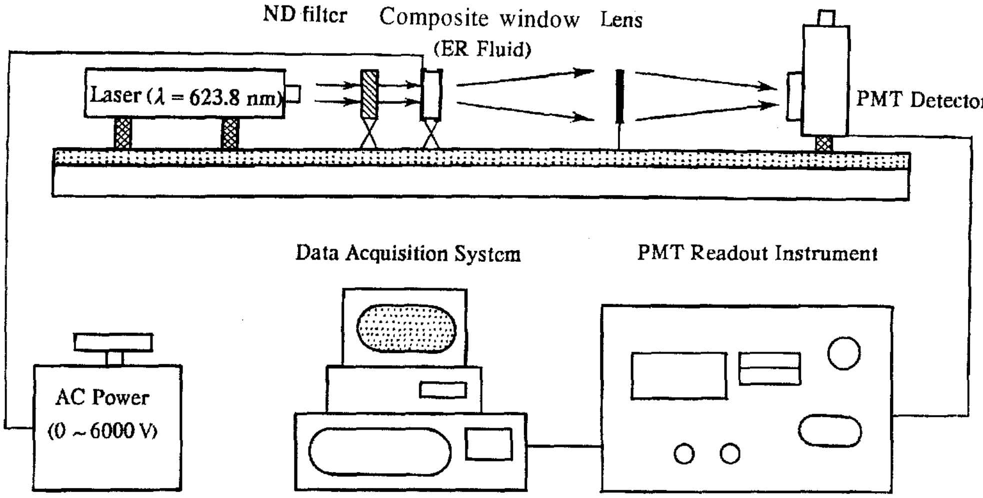

Fig. 2. Schematic of experimental apparatus.

system interfaced with an IBM microcomputer, thus allowing real-time monitoring while simultaneously recording the transferred light intensities.

The ER fluid employed in the present experiments consisted of crystalline zeolite particles suspended in phenylmethyl polysiloxane silicon oil. The mean particle diameter, as reported by the manufacturer, was $8 \pm 2\ \mu$. The dielectric constant of the silicon fluid was 2.95. These micron sized particles (specific density 1.1) were mixed completely with the carrier silicon oil (specific density 1.11) to make the sample particles almost neutrally buoyant in the fluid. This particle/fluid combination ensured a relatively stable composition of ER fluid.

Corroborative evidence of dynamic fibration process in ER was obtained through direct microscopic observations under a Zeiss microscope system. The electrically-induced particle-chains inside the medium were observed to align with the local electric field vector. This electrically-induced fibrous structure was established by the balancing forces acting upon it, where the electric force tended to maintain the fibration while the thermally induced and mechanical disturbances tended to disorient and break up the particle-chains. Once the field was removed, it took some time for Brownian motion to restore the initial random structure. These microscopic observations enabled us to better understand the fundamental mechanisms that characterize the radiation transfer control process in the ER fluid.

A sequence of experiments was performed for various controlling parameter values (i.e., f_v, v, and L). First, measurements of transmitted light from the composite window were made to obtain transmittance with ER fluid particle concentrations varying from 0.5% to 10% and the applied electric voltage varying from 250 V to 2000 V. This was followed by the experiments where four different pathlengths ranging from 0.5 mm to 2 mm were adopted for the composite window, while holding the particle concentration constant ($f_v = 1\%$) to further study the effect of field strength (V^*). These parameters and their ranges are determined based on the consideration of practical application as well as the measuring instrument capability.

All data of transmittance reported in this paper are normalized by the reference value I_0. I_0 is the light intensity transmitted through the composite window filled with pure silicon oil ($f_v = 0\%$). Since the PMT signal is dependent on both the internal bias supply voltage and the detection optics, calibrations were conducted to determine the value of I_0 with PMT bias supply voltage changing from -200 V to -543 V at which the 1×10^{-5} A saturation limit of PMT current was reached. To maximize the PMT sensitivity, the supply voltage of -600 V was chosen for the subsequent experiments which approximately corresponded to the reference value meter reading of 1.7×10^{-5} A for I_0.

The data acquisition technique for a typical run in the transmittance measurement is outlined. First, the freshly prepared ER sample fluid was injected into the composite window. Usually thirty minutes warming-up was necessary for the whole measuring system to reach its steady condition. Then the electric power unit was brought to the desired voltage and the data acquisition was executed at the sampling rate of 1/sec. The external electric power remained effective for fifteen minutes; after removal of the power, sampling was continued for another fifteen minutes to record the relaxation behavior of the composite window.

The overall accuracy of the measured transmittance in the current study is estimated within ±15%. This estimation includes various error sources introduced in the experiments, i.e., variation of the optical detector system; degrading of the glass quality thoughout experimental period; the fluctuation of high voltage output; the uncertainty of prepared sample fluid and reproducibility of experiments.

ANALYSIS

Consider radiation of intensity $I(0)$ impinging normally on a composite window featuring an ER fluid. As the radiation passes through the window, its energy is absorbed and scattered following Beer's Law (the cold-medium approximation with small scattering):

$$I/I(0) = e^{-KL} . \tag{1}$$

where, the extinction coefficient K is composed of two parts: an absorption coefficient a and a scattering coefficient σ ($K = a + \sigma$). As stated earlier, the ER fluid employed in this study lies primarily in the very low particle concentration region ($f_v < 10\%$), so we can simply assume that absorption (and hence the coefficient a) is mainly contributed by the glass and the carrier fluid. By defining the initial intensity I_0 and transmittance T ($I_0 = I(0)e^{-aL}$, $T = L/I_0$, I, I_0 are measurable quantities), we have:

$$T = e^{-\sigma L} . \tag{2}$$

We also notice that:

1) In transmittance measurements, there was found a linear dependence of T on the applied electric field strength V^* ($V^* = V/L$, $100 < V^* < 1000$).

2) Previous analysis of radiation transfer through fibrous material (Tong and Tien, 1983) adopted the similar relation developed for the particulate system: $\sigma - f_v$. Consider the difference between the $V^* \neq 0$ and $V^* = 0$ cases in radiation transfer mechanism, we thus propose a semi-empirical model in a two-equation formulation:

$$T = c_1 (V^* - V_0^*)\, e^{-c_2 f_v L} \, (100 < V^* < 1000 , \quad f_v \neq 0) , \tag{3}$$

$$T = c_3\, e^{-c_4 f_v L} \quad (V^* = 0 , \quad f_v \neq 0) . \tag{4}$$

The constants c_i, $i = 1, 4$ were determined by performing linear regression to equations (3) and (4) that can be re-written in the following formulations:

$$\ln [T/(V^* - V_0^*)] = \ln c_1 - c_2 (f_v L) , \tag{5}$$

$$\ln T = \ln c_3 - c_4 (f_v L) . \tag{6}$$

RESULTS AND DISCUSSION

Figures 3 and 4 present the microscopic behavior of the ER fluid ($f_v = 10\%$) when subjected to electric field with strengths of 0 kV/mm and 1.5 kV/mm respectively. The dark regions at right side of the pictures in Fig. 4 are images of the wire electrodes. These photomicrographs were obtained by video recording the response of ER fluid placed between the tips of two wire electrodes. The gap distance between the tips of the electrodes was 2 mm. Figure 3a clearly shows the randomly distributed particles inside the ER fluid. The scale of these photomicrographs

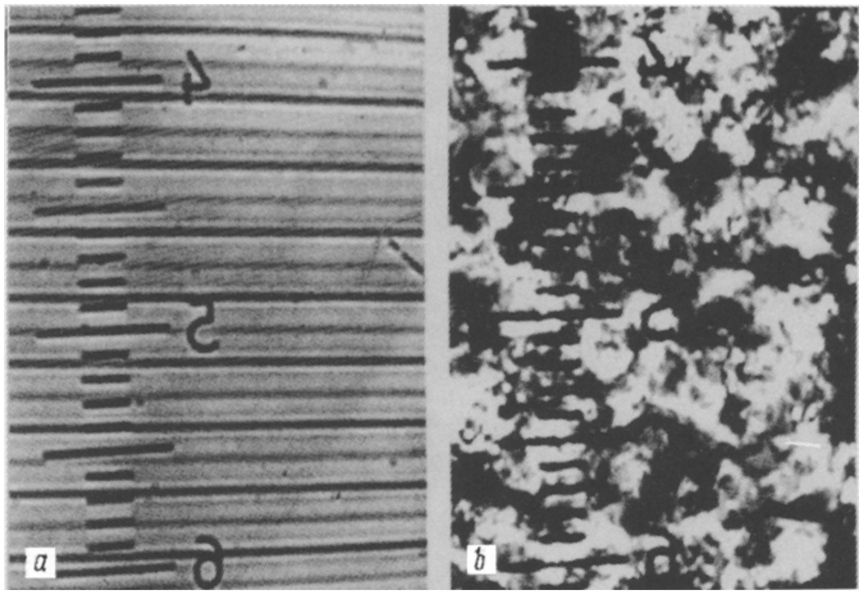

Fig. 3. a) photograph of micrometer (the gap distance: 1/100 mm); b) photograph of the ER fluid with an electric field strength of 0 kV/mm.

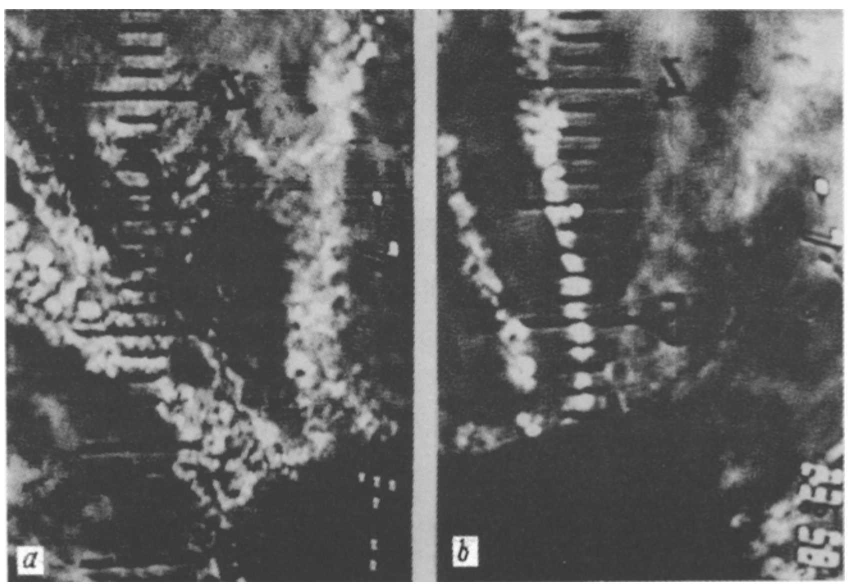

Fig. 4. Photographs of an ER fluid with an electric field strength of 1.5 kV/mm. a) multi-sphere width particle-chains; b) single-sphere width particle-chains.

can be found in Fig. 3b which shows the standard micrometer (1/100 mm per scale) taken under the same microscope setting conditions. In Figs. 4a and 4b, the electrically-induced particle-chains are observed to form around the electrode and aligned with the electric vector field. These particle chains could be multi-sphere width clusters (as in Fig. 4a) or single-sphere width chains (as in Fig. 4b) depending on local physical conditions (spatial and temporal). This finding is consistent with Klingenberg's result (Klingenberg, 1989) and will be discussed later in this paper. Thus, by applying an electric field to the ER fluid, the microscopic structure of this material can be substantially changed.

In Fig. 5, we present the typical transient patterns of transmittance, which was the trace of transmitted light through the composite window ($f_V = 1\%$, $L = 2$ mm). Also included in this figure is the profile of the applied electric field used to trigger the changes in transmittance. As the power was switched on, an electric field was

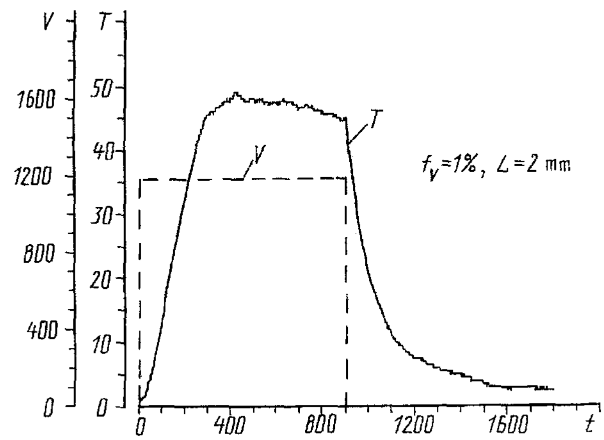

Fig. 5. Transient light transmittance patterns of ER fluid when subjected to an electric field.

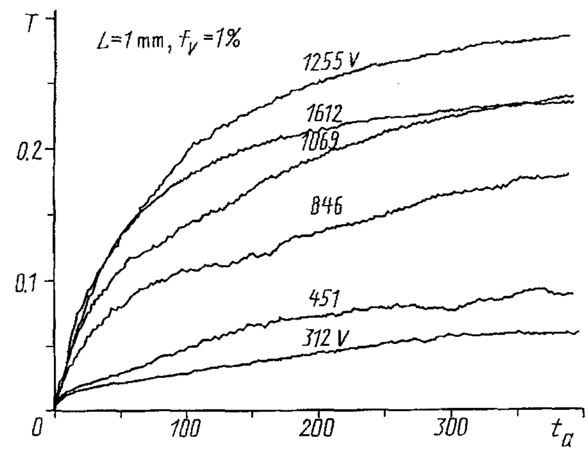

Fig. 6. Activation process of radiation transmission through ER fluid.

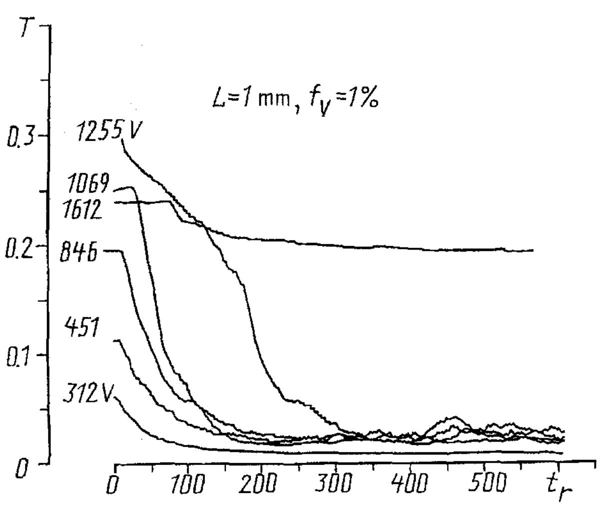

Fig. 7. Relaxation process of radiation transmission through ER fluid.

established across the sample fluid in the direction of the incident laser beam. Particles inside the sample fluid polarized almost immediately and came together into chains aligned with the electric field. This chain orientation structure which is parallel to 0^o orientation minimized the projected area of the particles on the plane normal to the incident beam, thereby increasing the transmittance. The process of this particle aggregate orientation was confirmed by the direct microscopic observation as discussed above. In this figure, the maximum transmittance of

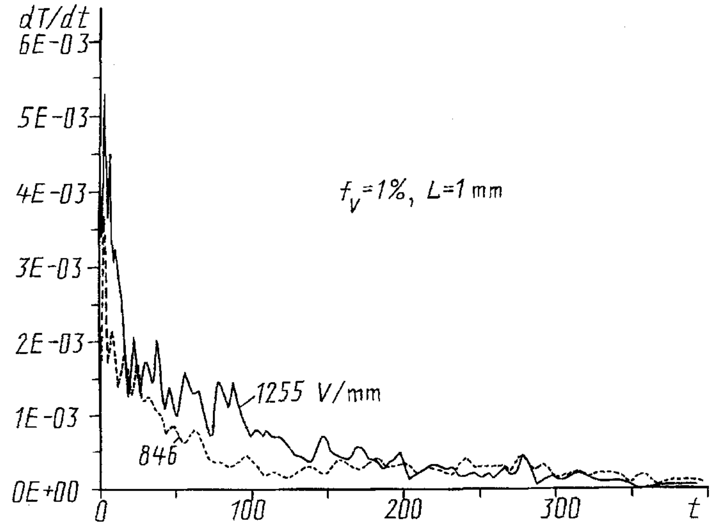

Fig. 8. Dynamic response of radiation transmission through ER fluid.

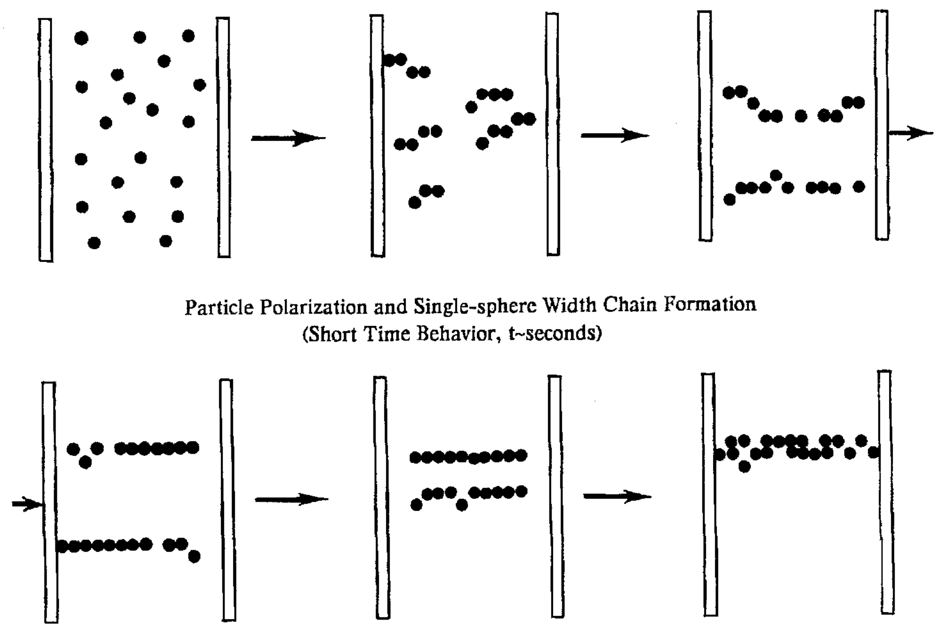

Fig. 9. Illustration of two-stage dynamic process of particle-chains formation.

ER fluids was found to increase by a factor of approximately 50 over that of the initial randomly oriented particles while the electric field required was 600 V/mm. When the field was switched off, Brownian motion quickly reestablished the initial random orientation. Thus, the transmittance returns to its initial value.

The time response and the nature of this electrically-induced fibration with its effect on radiation transmission was examined in Figs. 6, 7, 8, and 9. In Figs. 6 and 7, we present a complete set of transmittance response (the processes of activation and relaxation) with the electric field strengths ranging from 300 V/mm up to 1612 V/mm ($L = 1$ mm, $f_v = 1\%$). Figure 8 shows the dynamic response (taken as derivative of the transmittance) for two field strengths. It was found that in each case, the increase of the transmittance in response to the imposed electric field experienced two consecutive stages: the fast period ($t_a \sim 50$ sec) and the slow period ($t_a \sim 6$ min). The time derivative of the first period is approximately five times larger than that of the second period (see Fig. 8).

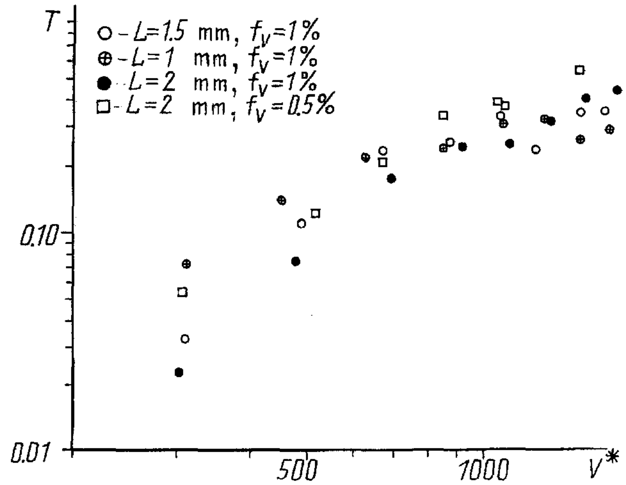

Fig. 10. Effect of electric field strength on radiation transfer through an ER fluid.

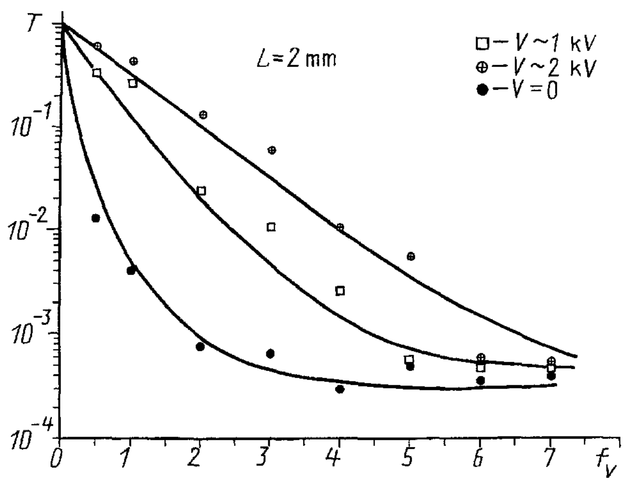

Fig. 11. Effect of particle concentration on radiation transfer through an ER fluid.

During the entire process, the transmittance initially increased quickly in the first stage and then changed into the second stage in which it increased gradually until it reached a quasi-stationary state that corresponded to the situation where the orientation of particle-chains were fully developed for a given strength (see Fig. 6). In Fig. 7, there appeared a time lag of transmittance in most cases when the electric fields were removed. Ideally, the distributed charges of polarized particles should release and thus the electrically-induced particle chains should break up instantaneously upon the removal of electric field, but it did not happen, because Brownian motion that is mainly responsible for restoring the particulate system to its random distribution was relatively weak. Thus, the time lag is seen in Fig. 8, especially when the previous established particle chains consisted mostly of multi-sphere width clusters due to the higher field strength.

In light of the findings via the transmittance measurement of this study and those published in the literature via the numerical simulation of ER effects (Klingenberg et al., 1989), we may postulate a physical mechanism of controlling radiation transfer through the ER fluid based composite window as illustrated in Fig. 9. In a two-dimensional composite window filled with neutrally buoyant, non-conducting, monodispersed colloidal suspension (ER fluid), the applied electric field induces instantaneously polarization forces between the particles and between the particle and the electrode walls. The immediate effect is the formation of small, short possibly slightly bent and single-sphere width particle chains (fast period). Correspondingly, the projected area of the particles on the plane normal to the incident radiant rays is reduced, thereby increasing the radiation transmission; as time proceeds, the interactions between the formed single-sphere width particle chains gradually become dominant and give rise to formation of multi-sphere width particle chains and/or possibly redistribution of the

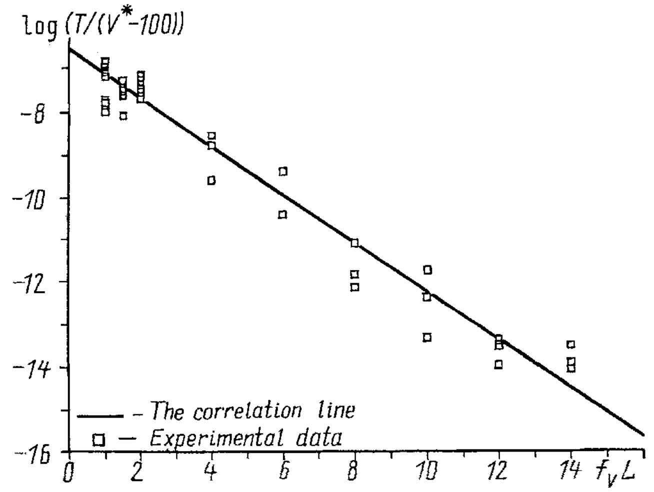

Fig. 12. Overall correlation of radiation transmission model for ER fluid.

polarized charges on those chains (slow period), thereby further reducing the projected area of particle-chains normal to the incident beam and increasing the radiation transmission. This second behavior of ER fluids is strongly dependent upon the applied electric field strength as well as the particle volume fraction. Thus, radiation heat transfer through the ER fluid based composite window can be controlled by varying the controlling parameters of the electric field and particle concentration inside the ER fluid (V, f_v, and L). Particles inside the ER fluid are also subjected to other forces such as Brownian forces and the hydrodynamic resistance. At a certain high voltage level, these forces become significant and tend to disorient the established particle chains, and the radiation transmission would slightly decrease (as seen in Fig. 6).

To further study the functional dependence of radiation transmittance based upon the controlling parameters of V^* and f_V, measured transmittance was plotted versus V^* and f_V and is presented in Figs. 10 and 11. In Fig. 10, it is clearly seen that an increase in the electric field strength led to an increase in transmittance. There appears to be a linear relation between T and V^*. However, when V^* exceeds a certain value, i.e., 1000 V/min, the slope of this increase tended to decrease. This phenomenon can be interpreted from the mechanism postulated previously. For a particular particle concentration, if the electric force was weaker, the particle chains mostly consisted of single-sphere particle width chains, were looser, and may even relieve the hold of the field on the particles in the chain. Thus, increasing the field strength could force the particle-chain strictly parallel to the incident beam and could also create more multi-sphere width particle chains. Eventually, at sufficient strong field strength, the electric force effectively eliminated the disorientation and transmittance became independent of the electric field strength.

In Fig. 12, we show the effect of particle concentration on transmittance for three electric field conditions. These curves clearly demonstrate the difference between radiation transfer through the particulate medium ($V^* = 0$) and through the electrically controllable fibrous ER fluid ($V^* \neq 0$). When $V^* = 0$, transmittance declines exponentially which agrees with the classic Mie theory ($K \sim f_V$ and $T \sim e^{-KL}$). However, this relation cannot be applied directly to the ER fluid once the electric field is imposed (see Fig. 12).

Note that as the particle concentration exceeded 6%, the effect on transmittance by applying electric field to ER fluid tended to be negligible. This is also consistent with the mechanism postulated before. If the particle number inside the fluid was sufficiently large, the interactions between particles and particle chains became significant. Eventually, the multi-sphere width chain clusters stacked next to each other in a compact space, thereby minimizing the effect of radiation enhancement. On the other hand, if the transmitted radiant intensity was close to the detector limit (currently, $T_{\text{limit}} = 0.5 \times 10^{-4}$), the measurement became less reliable due to the lower S/N ratio. Nevertheless, the effect of controlling radiation transfer was minimized at relatively higher particle concentrations. From the application point of view, one would conclude that there is an optimal ER fluid concentration to be used to control radiation heat transfer which should be relatively small.

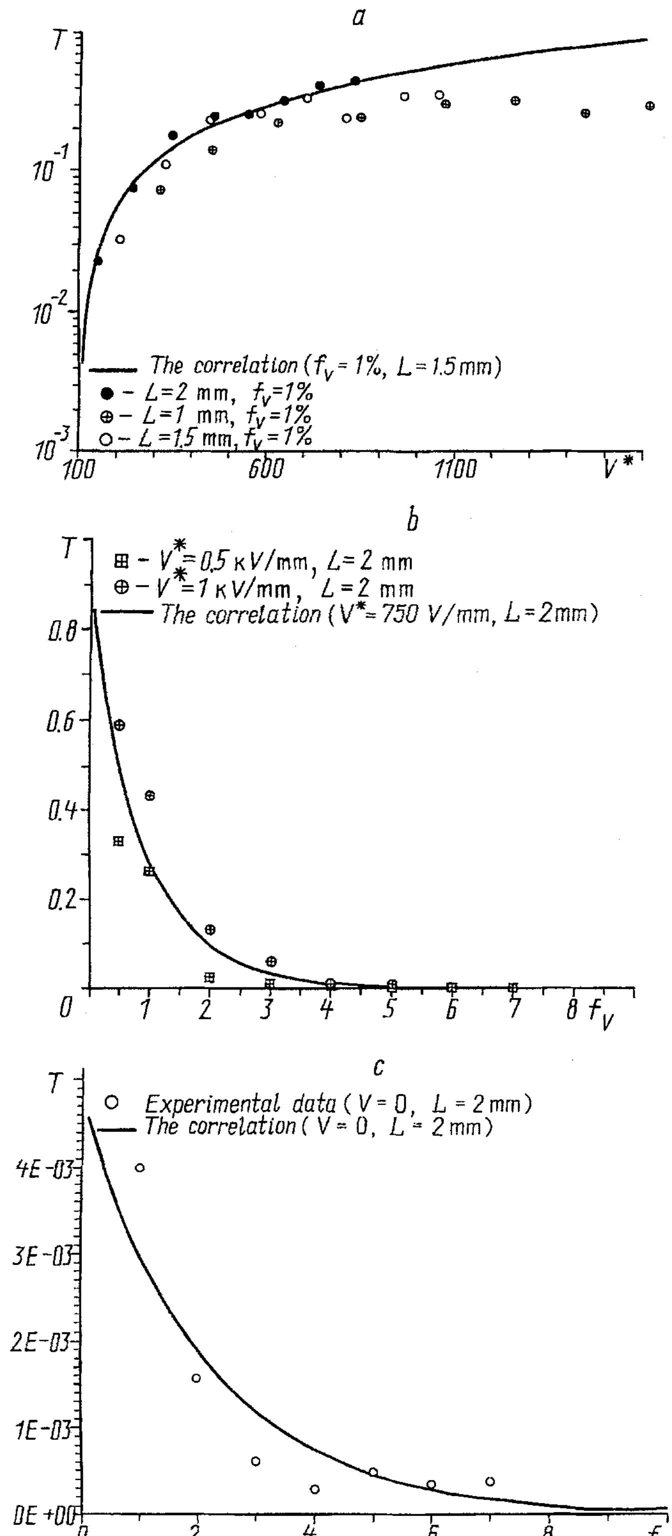

Fig. 13. Comparison between the model and measured transmittance: (a) field strength effect; (b) particle concentration effect; and (c) zero voltage condition.

To test the validity of the proposed semi-empirical model (equations (3) and (4)), experimental data were used to determine the constants c_1, c_2, c_3, and c_4 in model equations. Shown in Fig. 13a is the correlation line (Eq. 3) and the measured T taken at various physical parameters (V^*, f_v, and L). In this figure, the maximum error is found within 12%. Further comparisons were made between the derived model and experimental data (see Figs.

13c and 13d). Reasonable agreement was found in these figures. This suggests that radiation transfer through ER fluid based composite window may be correlated by an overall model for applications.

Acknowledgement

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NOTATION

a, absorption coefficient; c_i, constants in equations (3) and (4), $i = 1, 4$; f_v, particle volume fraction, %; I, measured light intensity; I_0, initial light intensity, $I_0 = I(0)e^{-aL}$; $I(0)$, intensity of incident beam; K, extinction coefficient, 1/mm; L, extinction pathlength, mm; t, time, sec; t_a, activation time, sec; t_r, relaxation time, sec; T, transmittance, $T = I/I_0$; V, voltage of the applied electric field, V; V^*, field strength of the applied electric field, V/mm; V_0^*, reference field strength, 100 V/mm; σ, scattering coefficient.

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