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HEAT TRANSFER AND FRICTION COEFFICIENTS FOR DILUTE SUSPENSIONS OF ASBESTOS FIBERS

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Abstract—Experiments were conducted to determine heat-transfer coefficients and friction coefficients for dilute suspensions of asbestos fibers flowing in a smooth, and in a rough tube. For the given tubes, drastic reductions were observed in both coefficients for a certain range of Reynolds numbers. Beyond this range, the values applicable to the pure fluid were approached asymptotically. It has to be realized, however, that even for a given concentration the Reynolds number by itself is not sufficient to fully describe the flow conditions and that at least one additional parameter, probably one based on the wall shear, will be needed.

NOMENCLATURE

C_F, friction coefficient ($C_F = 2\tau_0/\rho V^2$);
C_H, heat-transfer coefficient, $C_H = q/\rho Vc(T_w - T_B)$;
d, tube diameter;
Pr, Prandtl number;
q, heat-transfer rate per unit area;
Re, Reynolds number for flow in tube;
T_B, bulk temperature of fluid;
T_w, temperature at inside of wall;
u_τ, shear velocity $u_\tau = (\tau_0/\rho)^{1/2}$;
V, average velocity in tube;
y, distance from pipe wall;
y^*, dimensionless distance from pipe wal' ($y^* = yu_\tau/v$).

Greek symbols

ε_s, equivalent sand grain roughness;
v, kinematic viscosity;
ρ, fluid density;
τ_0, wall shear stress.

INTRODUCTION

EVER since the discovery by Mysels [1] and Toms [2] that certain additives can cause drag reduction in turbulent flows a considerable effort has been devoted to this phenomenon. Analytical and experimental studies have been performed both: in order to understand the mechanism responsible for the effect and to provide information for engineering design. The largest portion of the work has been devoted to dilute solution of polymers. Excellent reviews of most of these results have been provided by Hoyt [3] and by Virk [4]. Much of the findings of investigations involving dilute suspensions have been ably assembled in a survey by Radin, Zakin and Patterson [5]. Most of the studies performed and cited in the foregoing references concern drag reduction and are not concerned with heat transfer.

The present experiments were carried out with dilute suspensions of asbestos fibers in water. The work was initiated subsequent to an extensive study on the heat transfer and fluid friction in dilute polymer solutions. It was thought that the results obtainable with the fiber suspension might add to our understanding of the general mechanism of drag reduction. In particular, it was thought that asbestos fibers might be more resistant to damage than polymers and that it would simplify the interpretation of the data if the possibility of deterioration could be excluded. In addition to these more basic aspects the project was also based on the desire to add to the available information on complex fluids including polymer solutions, suspensions, sludges and even granular media. Such complex fluids are presently being moved and processed in large quantities in the chemical industry and in the course of food processing. With further growth in these industries the demands are likely to increase for more economical equipment using heat effectively. To develop such equipment the designer will need to be aware of the special characteristics of some of these fluids.

EXPERIMENTAL INSTALLATION

The experimental installation is basically the same as that used by Debrule [6]. The test fluid is first drawn into a large supply cylinder by a receeding piston. The fluid is then discharged through the test section and collected in a receiver tank. This "once-through" system was selected over a circulating loop arrangement in order to avoid possible damage to the test fluid by any circulating pump. Experiments were conducted with two test sections, a smooth tube and a rough tube. The nominal dimensions of the tubes were $\frac{3}{8}$ in (0.95 cm) for the diameter and 18 in (45.8 cm) for the length. The equivalent sand grain roughness, ε_s/d, for the rough tube was 0.0488. The tubes are the very ones originally prepared by Dipprey [7] and used extensively also by Debrule [4] and more detailed dimensions are given in these references. The tubes are heated electrically by passing current through the tube walls and the heat-transfer rate was calculated from the known electrical dissipation rate. Thermocouples

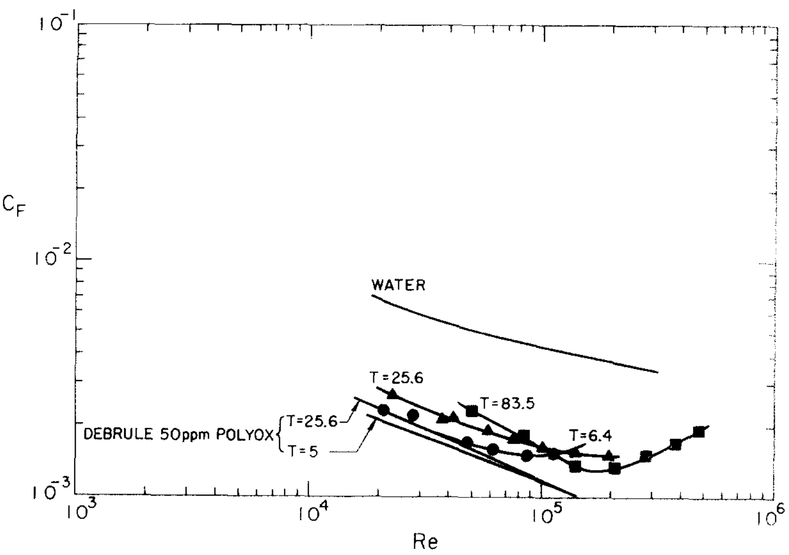

FIG. 1. Friction coefficient vs Reynolds number for 300 ppm asbestos suspension in a smooth tube. The numbers 6.4, 25.6 and 83.5 indicate temperatures in °C and correspond to $Pr = 10.7$, 6.16 and 2.07 respectively.

were placed at several stations along the wall and their readings were used to determine the inside wall temperatures. In addition inlet and outlet temperatures were measured, and the flow rate was determined from the rate of advance of the driving piston.

As indicated earlier the test fluid consists of a suspension of asbestos fibers in water. Asbestos fibers are very special in that they are extremely thin (of the order of $5 \cdot 10^{-8}$ m) and have a very large ratio of length to diameter. The suspension has to be prepared with special care to prevent the fibers from sticking together and from forming thick strands or clumps as much as possible. The present project was aided greatly through the courtesy of Turner Brothers Asbestos Co., who provided well made concentrated suspensions (about 2% asbestos in chrysotile form) which then only needed to be diluted to the required concentrations for the present tests, which were 50 and 300 ppm respectively. A surfactant (OT) was added in the preparation of the suspension. As was shown by separate tests, the surfactant by itself does not have any measurable effect on the heat transfer or friction characteristics of the fluid.

PRESENTATION OF EXPERIMENTAL DATA

1. *Smooth tube*

As a first step in the experimental procedure measurements were made to determine the heat-transfer coefficients and friction coefficients for pure water in the smooth tube at various Reynolds and Prandtl numbers. These results could then be compared to those obtained earlier with the same tube [6], and this comparison could then serve to some extent as an overall calibration. The differences in the friction coefficient were undetectable (below about 1%) and the same can be said for the heat-transfer coefficients at two of the Prandtl numbers ($Pr = 2.07$ and 6.16) which were selected for the present series of tests. At a Prandtl number of 10.7 the coefficients determined for the present tests were about 10–15% above those reported by Debrule [6]. This point was not considered to be of major concern, however, especially as the effects of interest in the present investigation were those producing changes of factors of two or even more.

The results obtained with a suspension at a concentration of 300 ppm are shown in the next two figures. In Fig. 1 C_F is given as a function of Re for various water temperatures. Several different temperatures were selected, as each determines a different Prandtl number. For comparison the curve for the friction coefficient for pure water is also shown.

The most striking feature of the graph is probably the fact that it indicates reductions in friction by a factor of the order of 3 for a fairly wide range of Re. The drag reducing ability of asbestos had, of course, been determined by earlier investigators, see for example [8, 9]. One may further note a tendency for C_F to increase at the higher Reynolds numbers, and one may speculate that the stress reducing ability might disappear completely if the Re were to be increased still further. This condition has actually been observed for a weaker suspension containing only 50 ppm of asbestos. This loss of drag reducing ability has been observed previously with polymer solutions in rough tubes [6]. At that time the effect was thought to be caused most probably by deterioration of the polymer at high shear stresses. It was reasoned further that asbestos fibers might be less likely to incur damage in this way. Apparently, however, this expectation is not realized and the effectiveness of the asbestos suspension also seems to be subject to deterioration. Examining the graph (Fig. 1) further it is also surprising at first glance that the curves for C_F vs Re differ for the three temperatures at which tests were performed. It was ascertained that the differences at the various tem-

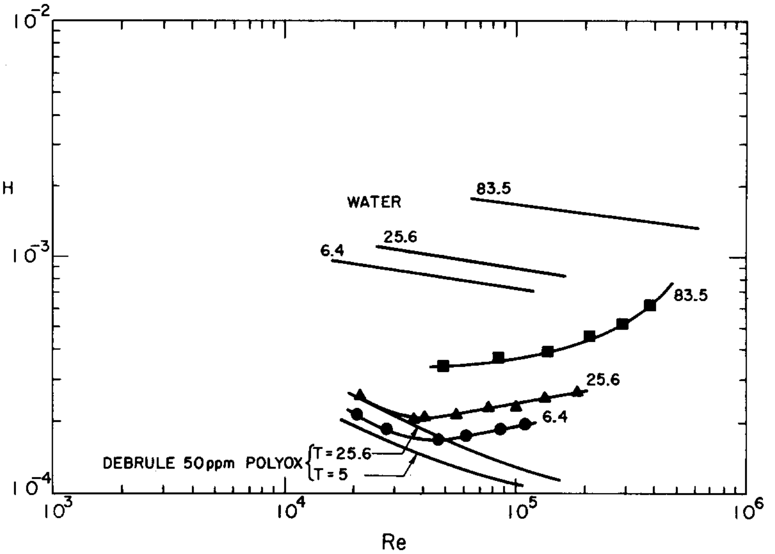

FIG. 2. Heat-transfer coefficients vs Reynolds number for 300 ppm asbestos suspension in a smooth tube. The numbers 6.4, 25.6 and 83.5 indicate temperatures in °C and correspond to $Pr = 10.7$, 6.16 and 2.07 respectively.

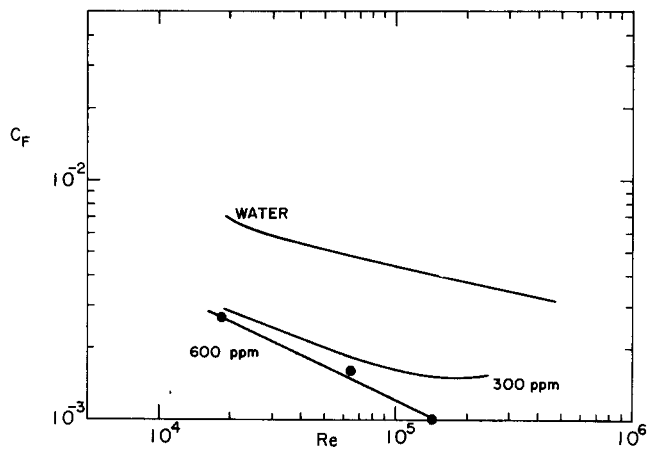

FIG. 3. Comparison of friction coefficients in a smooth tube for a 300 and a 600 ppm asbestos suspension at 25.6°C, corresponding to $Pr = 6.16$.

peratures were not caused by experimental errors or lack of repeatability, and that the differences are indeed real. In any attempts to interpret these differences it will be well to recall that each temperature represents a different viscosity and that consequently the wall shear at a given Re is a function of the temperature.

Purely for comparison two curves for the friction coefficient of a dilute polymer solution [6] (50 ppm of polyethylene oxide in water) were also entered on Fig. 1. They show that the order of friction reduction obtainable with the two particular fluids is of the same order of magnitude.

The heat-transfer results for the 300 ppm suspension are shown in Fig. 2. For a certain range of Re, the heat-transfer coefficient is reduced by as much as a factor of 4 or 5. Similar to the behavior of C_F, beyond a certain Re the heat-transfer coefficient C_H again increases with Re and the reduction effect may well disappear completely for sufficiently high Re. Heat-transfer results for a 50 ppm polymer solution are shown for comparison and analogous to the friction data, the reduction in heat transfer is similar for the two fluids.

A few exploratory experiments were also conducted with a higher concentration of asbestos fibers, 600 ppm. Data were taken at one temperature only (25.6°C) and the results are shown in Figs. 3 and 4. It is seen that the friction coefficient (Fig. 3) is reduced somewhat below those obtained with the 300 ppm suspension. An additional reduction is also achieved for C_H, and it is particularly noteworthy that for 600 ppm there is no reversal of the slope in the curve for C_H vs Re, within the range of the experiments. The heat-transfer curve (Fig. 4) shows a similar behavior.

2. *Rough tube*

The rough tube was produced so as to have surface protrusions similar to sand grains. The ratio of the equivalent grain size ε_s to the diameter is 0.0488, where

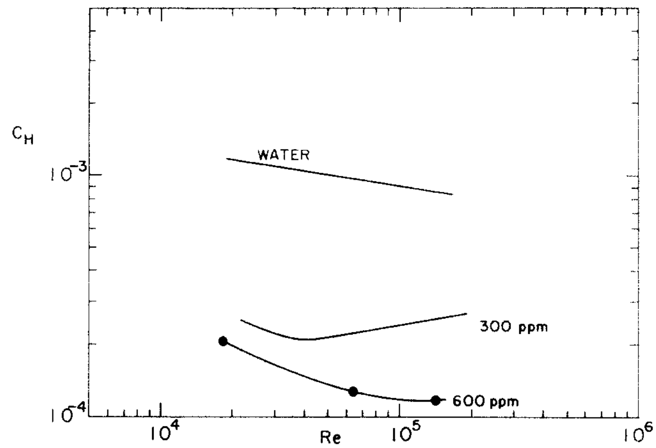

FIG. 4. Comparison of heat-transfer coefficient in a smooth tube for a 300 and a 600 ppm asbestos suspension at 25.6°C, corresponding to $Pr = 6.16$.

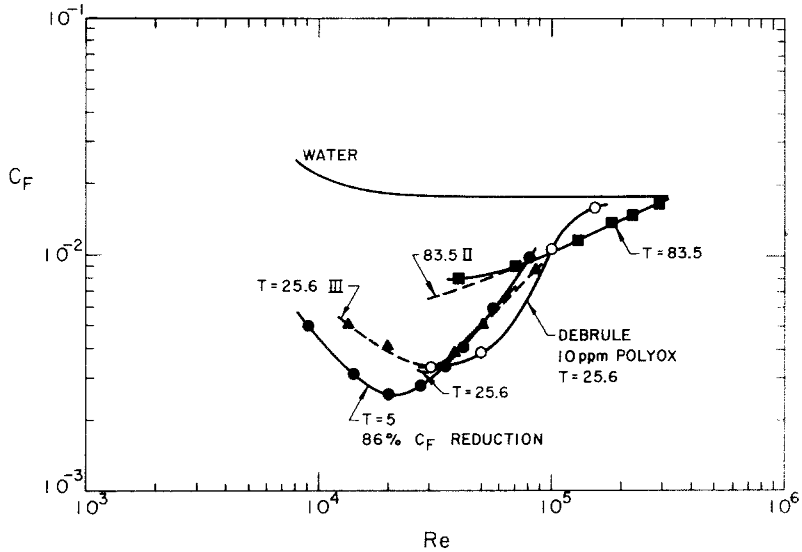

FIG. 5. Friction coefficient vs Reynolds number for a 300 ppm asbestos suspension in a rough tube. The numbers 5, 25.6 and 83.5 indicate temperatures in °C and correspond to $Pr = 10.8$, 6.16 and 2.07. Roman numerals indicate repeat runs.

ε_s is determined by matching the actual friction coefficient to that obtained by Nikuradse (see e.g. [10]) with sand grains of a size to give the same value of ε_s/d. The friction coefficient of the tube for pure water is shown on the graph (Fig. 5). For $Re > 2 \cdot 10^4$ the flow is essentially in the fully rough regime and C_F is about 0.018. At $Re = 10^5$ this is about 4 times the value for a smooth pipe, indicating a high degree of roughness (equivalent to about 3 millizwickies, as suggested by von Karman [11]). As may be seen from the graph (Fig. 5) the friction factor for the suspension is drastically reduced for certain ranges of Re. The reduction reaches a maximum of a factor of 7. As for the smooth tube the reduction effect tends to disappear as Re increases. The friction coefficient does, in fact become asymptotic to the value for pure water within the range of the present experiments. Data taken at different temperatures (and therefore at different viscosities) again define separate curves. To check the reproducibility of the data, experiments were repeated with a batch of the suspension prepared separately and at a different time. The dashed curve marked II indicates these additional data for the temperature of 83.5°C and that marked III is the corresponding one for the temperature of 25.6°C. To provide a general basis of comparison some results obtained with a very dilute polymer solution are also given in the graph.

Heat-transfer data for the asbestos suspension in a rough tube are shown in Fig. 6, with corresponding data for pure water indicated by the solid lines. Heat-transfer reductions by an order of magnitude are noted for $Pr = 10.8$ and 6.2 for Reynolds numbers in the range between 10^4 to $3 \cdot 10^4$. For Re beyond about $6 \cdot 10^4$ the reduction effect rapidly diminishes and the data for the suspension tend to become asymptotic to those for pure water. The complete set of data for $Pr = 10.8$ ($T = 5$°C) and for $Pr = 6.2$ ($T = 25.6$°C) were repeated with separately prepared batches of suspension as for the

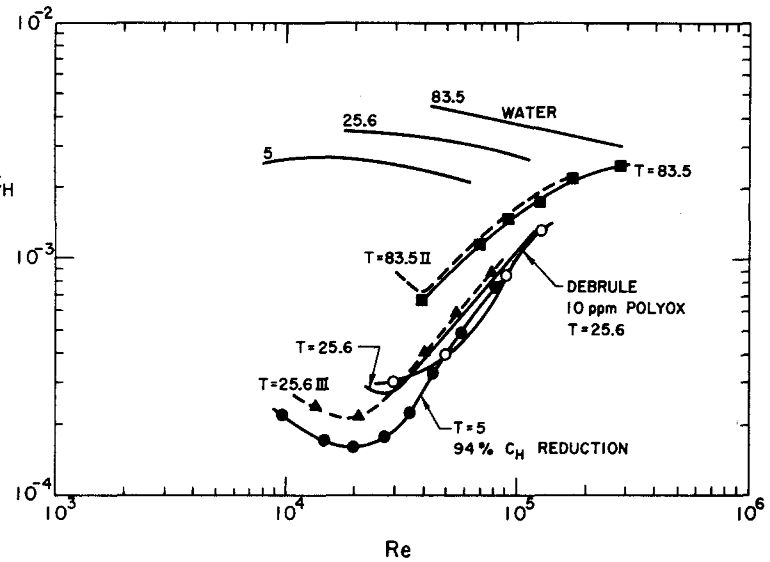

FIG. 6. Heat-transfer coefficient vs Reynolds number for a 300 ppm asbestos suspension in a rough tube. The numbers 5, 25.6 and 83.5 indicate temperatures in °C and correspond to Pr = 10.8, 6.16 and 2.07. Roman numerals indicate repeat runs.

friction data. The separate sets are again labelled by the numerals II and III. Considering the steps in the preparation of the suspension, the repeatability is thought to be remarkably good.

A few experiments were again conducted with a suspension containing 600 ppm of asbestos. The additional reduction over that obtained with a 300 ppm solution is low at the low Re range, but considerable at the higher Re. For the rough tube, however, even the strong suspension shows a reversal of slope for both C_F and C_H, and the trend of the curves indicates that the reduction effect will probably vanish completely at higher Re as is suspected for the lower concentrations.

DISCUSSION

In discussing the data it is perhaps appropriate to emphasize again that asbestos fibers in water may bring about very major reductions in the heat-transfer coefficient and in the friction coefficient, both in rough and smooth tubes. The conditions under which the reduction will take place are limited and in the present experiments it occurs only for a certain range of Reynolds numbers. From many previous studies [5] as well as from the results of the present work, it has become evident that, even for a given concentration, the Reynolds number is not the only parameter determining the behaviour of the fluid. There should be at least one other parameter, most likely a dimensionless ratio of the wall shear velocity $[u_\tau = (\tau_0/\rho)^{1/2}]$ divided by a characteristic of the suspended medium. The data presented will therefore, have to be used with great care in any design application and the graphs of C_F or C_H vs Re should not be used with the generality that applies to the graphs for pure substances.

Next a comment has to be made in regard to the repeatability of the results and to the comparability to the work of others. It was mentioned earlier that unexpectedly good repeatability was achieved in the present series of tests, leading to maximum variations of about 20%. This was accomplished by using asbestos from a single source and carefully following the same steps in preparing the solution. It is well known that asbestos from certain other sources may require concentrations of 2000–3000 ppm to achieve comparable reduction in friction [5, 9]. To examine the sensitivity of the present suspension repeated tests with the same solution were also performed. After a run in the rough tube, for example, the solution was rerun in the same tube 0.5 h after the initial test. In that case the ability of the suspension to reduce friction was definitely diminished. Yet, after a recovery period of a day, the suspension performed in a very similar fashion than a fresh solution. The heat-transfer coefficient of the reused suspension was also raised somewhat but to a much lesser extent, and it did not seem to recover after the one day interval. These results are mentioned here not because of any general validity that they may have, but merely to indicate how complex the fluid is and how results may be affected by circumstances which have no influence in the case of pure water and many other fluids.

In the hope of gaining some insight into the behavior of the fibers in suspension a number of electron photomicrographs were taken of which one is shown in Fig. 7. The photograph was prepared by taking a drop of the suspension and placing it on the grid holder of the microscope. The sample is then placed in a chamber which is evacuated before the photograph is taken. There is no water present, therefore, during the photographic process, and the fibers may not be in quite the same arrangement which they assume while in the suspension. Nevertheless, they probably do give a useful indication of what their distribution might be in the fluid. The picture shows first of all that there are many very thin fibers with thickness of the order of a few hundred angstroms (1 Å = 10^{-10} m). Others are much

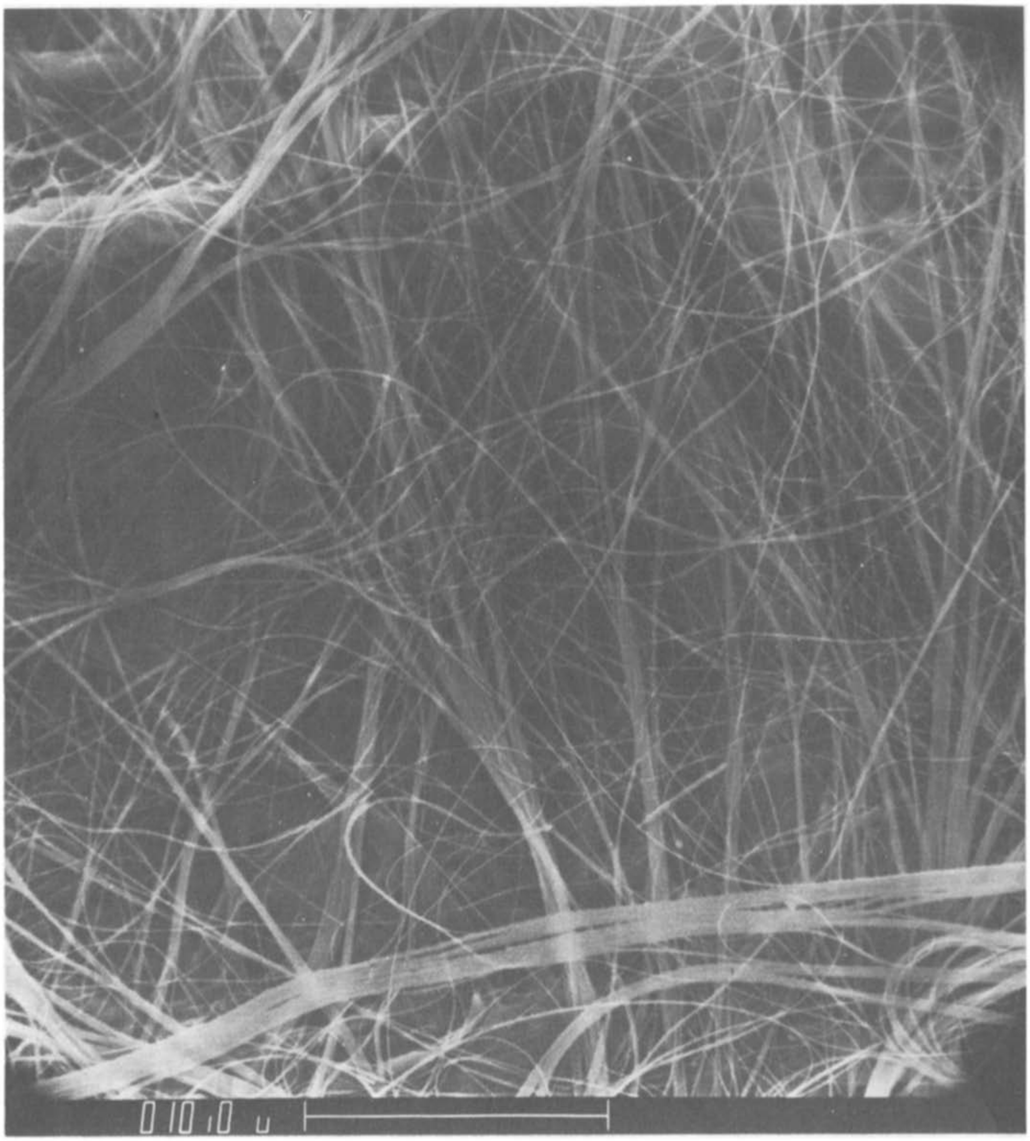

FIG. 7. Photograph of asbestos fibers from a 300 ppm suspension. Length of bar is $10\,\mu$ (10^{-5} m).

thicker, and probably consist of a number of fibers stranded together. Perhaps most importantly, however, it appears that the various fibers and strands form a rather dense mesh in which the motion of each fiber is certainly influenced by its connection to the mesh. One might well imagine the mesh as being similar to steel wool, or even finely divided real wool. The mesh probably moves with the fluid in some way.

Having in mind a general picture of the manner in which the fibers are distributed in the fluid, one may wish to speculate on how they might interact with the fluid. In this connection the description of the flow near the wall is recalled as given by Kline [12]. In his description Kline points out that in turbulent flow longitudinal vortices are formed in the wall layer in a random fashion but with a fairly definable average period and spacing. The vortices lift fluid from the wall region toward the center of the flow. By continuity, fluid from the outer region will flow towards the wall. The action of the vortices, in brief, promotes the exchange of fluid as well as of momentum and heat. The scale of the vortices is large compared to some of the wall layer measures, and the fluid from the vortices is moved to distances of the order of $y^* \approx 400$. One may well imagine then that the asbestos mesh interfers with the motion caused by the vortices and that it will therefore create a major reduction of the exchange mechanism. Applying the concept of a mesh-like structure to a polymer solution, could also explain how these really rather different additives (a long chain polymer such as polyetheylene oxide and asbestos fibers) might produce such similar effects on heat transfer and friction.

There is in addition evidence that polymers and other drag reducing additives change the flow picture near the wall but leave the flow in the core largely unchanged. This may also be explainable by assuming that the additives and the mesh-like structures they form are of a scale so as to interact effectively with the vortices in the boundary layer, but not with other turbulent velocity fluctuations. Furthermore, as mentioned earlier, polymer solutions seem to lose their ability to reduce drag at high shear stress. This loss was ascribed to a deterioration of the polymer at high shear stress. It was expected that asbestos fibers might be able to withstand such stresses and not show any effects of deterioration. As the present results have shown (see e.g. Fig. 1) the fiber dispersions showed the same trends at high shear. This may also possibly be explained in terms of a mesh that may be sheared and torn, and the limiting force for such failure does not depend directly on the strength of the components of the mesh, but on the interconnections. In the present case this means that the shear stresses developed at high *Re* were high enough to damage the polymer solutions as well as the fiber suspension.

The last feature to be mentioned has to do with the ratio of $2C_H/C_F$. For water (or any Newtonian fluid) this ratio tends to unity when the Prandtl number goes to unity. In Fig. 8 $2C_H/C_F$ for the smooth tube is plotted against Prandtl number for both the 300 ppm asbestos suspension and for pure water. The data for pure water were also taken from the present experiments. Whereas the curve for water tends towards 1.0, the one for the 300 ppm tends towards a much lower value, such as 0.5 or 0.6. This is an indication that the often used Reynolds analogy may not apply to the suspension and that momentum is transported in a different way from heat even for $Pr = 1.0$. Thinking in terms of a mesh one can understand that it may well inhibit fluid exchange and, at least at $Pr = 1$, this should lead to equal reductions in heat and momentum exchange. However, in addition the mesh structure may well offer a mechanism for transmitting forces and thereby bring about further momentum exchange. At the same time the mesh does not provide any equivalent mechanism for the transfer of heat, as any conduction paths along the fibers are likely to be very long and poor. This then gives an indication of the reasons that may make the Reynolds analogy inapplicable for the type of suspension under discussion.

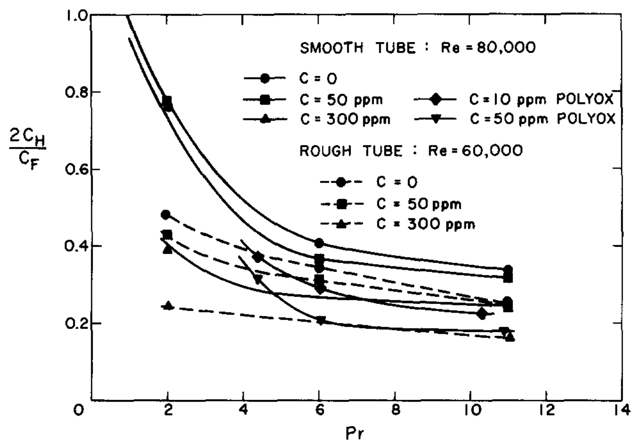

FIG. 8. Comparison of $2C_H/C_F$ vs *Pr* for pure water, Polyox solutions and asbestos fiber suspensions.

CONCLUSION

A rather broad and systematic experimental study was conducted of very dilute suspensions of asbestos fibers in water. The results show that very drastic reductions in friction and heat-transfer coefficients are obtainable. These reductions occur, however, for certain flow conditions only. In part these flow conditions depend, of course, on the Reynolds number and the Prandtl number. But even for a given additive and a given concentration there is at least one additional parameter which has a major influence. This parameter is expected to be one based on the wall shear. The interaction of these parameters is not fully understood at this time and neither are the experimental data extensive enough to allow the prediction of friction coefficients and heat-transfer coefficients in a general way. Designers of hydraulic circuits and heat exchange equipment, however, should be aware of the possibility that there could be wide variations from the heat-transfer rates or friction drops that one would predict for a pure fluid. The type of applications in which this may be of importance are not so much those in which the additives are mixed into the fluid intentionally, but those applications in which fluids are being handled which inherently contain such ingredients as polymers and fibers. Substances processed by the food and chemical industry might well fall into this category and one might imagine, for example, that a heat exchanger designed according to presently accepted practice may give quite unexpected results in operation with some of these fluids.

Some mechanisms were proposed which might explain several experimental trends which were observed. These proposed mechanisms are, of course, entirely qualitative and speculative. They would, however, allow a consistent interpretation of some of the special characteristics of the suspension that have been observed. The thoughts on this subject have been presented in the hope that they will serve as basis for planning further studies on fluids such as the dilute asbestos fiber suspensions.

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COEFFICIENTS DE TRANSFERT THERMIQUE ET DE FROTTEMENT POUR DES SUSPENSIONS DILUEES DE FIBRES D'AMIANTE

Résumé—Des expériences sont conduites pour déterminer les coefficients de transfert thermique et de frottement pour des suspensions diluées de fibres d'amiante dans un tube lisse et dans un tube rugueux. On observe une forte réduction des deux coefficients pour un certain domaine de nombre de Reynolds. Au delà de leur domaine, les valeurs applicables au fluide pur sont approchées asymptotiquement. On constate que même pour une concentration donnée, le nombre de Reynolds ne suffit pas pour décrire complètement les conditions d'écoulement et qu'au moins un paramètre supplémentaire, probablement basé sur le frottement pariétal, est nécessaire.

WÄRMEÜBERGANGS- UND WIDERSTANDSKOEFFIZIENTEN VON VERDÜNNTEN SUSPENSIONEN AUS ASBESTFASERN

Zusammenfassung—Es wurden Experimente durchgeführt, um in einem durchströmten glatten und in einem rauhen Rohr für verdünnte Suspensionen aus Asbestfasern Wärmeübergangs- und Widerstandskoeffizienten zu ermitteln. In einem bestimmten Bereich der Reynoldszahl wurde beide Koeffizienten eine beträchtliche Abnahme beobachtet. Die Werte für das reine Fluid wurden asymptotisch angenähert. Bei vorgegebener Konzentration reicht die Reynoldszahl nicht aus, um die Strömungsbedingungen zu beschreiben, es ist mindestens ein zusätzlicher Parameter—wahrscheinlich auf der Grundlage der Scherung an der Rohrwand basierend—notwendig.

КОЭФФИЦИЕНТЫ ТЕПЛООБМЕНА И ТРЕНИЯ РАЗБАВЛЕННЫХ СУСПЕНЗИЙ АСБЕСТОВЫХ ВОЛОКОН

Аннотация — Проведены эксперименты по определению коэффициентов теплообмена и трения разбавленных суспензий асбестовых волокон в гладкой и шероховатой трубах. Наблюдалось резкое уменьшение обоих коэффициентов в определенном диапазоне чисел Рейнольдса. За пределами данного диапазона значения для чистых жидкостей достигались асимптотически. Необходимо, однако, учесть, что при определенной концентрации волокон недостаточно одного числа Рейнольдса для описания режимов течения. Необходим хотя бы один дополнительный параметр типа напряжения сдвига на стенке.