Int. J. Heat Mass Transfer. Vol. 31, No. 9, pp. 1913–1921, 1988
Printed in Great Britain

0017-9310/88 $3.00+0.00
Pergamon Press plc

Heat transfer and friction coefficients for tomato puree

E. F. MATTHYS
Department of Mechanical and Environmental Engineering, University of California, Santa Barbara, CA 93106, U.S.A.

and

R. H. SABERSKY
Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA 91125, U.S.A.

(*Received* 6 *November* 1987 *and in final form* 12 *February* 1988)

Abstract—We believe that there is a need for engineering data involving fluids which are processed in large quantities, but which do not follow the laws of Newtonian fluids. Tomato puree is such a fluid and it was selected for the present investigation. Heat transfer and friction coefficients were obtained for a range of operating conditions and it was possible to present the results in the customary way by defining an apparent viscosity, and by computing a Reynolds number and a Prandtl number based on that viscosity. The apparent viscosity depends on the shear rate and this effect was taken into account. Additional experiments were conducted with tomato puree containing small amounts of polymeric additives. The experimental heat transfer and friction coefficients were compared with those of Newtonian fluids. It is hoped that the results will provide some guidance to the engineer who is faced with designing heat exchange equipment for complex fibrous fluids such as tomato puree.

INTRODUCTION

THROUGHOUT the development of fluid mechanics and heat transfer, by far the largest effort has been devoted to Newtonian fluids. This is, of course, both very appropriate and very justifiable as air and water are essentially Newtonian and the understanding of the motion of these fluids is central to our technological progress. The work on Newtonian fluids has been so successful that we are now able to predict the behavior of even very complicated flows and this ability has been crucial in the development of such modern systems as airplanes, ships, pipelines, rockets, turbines and jet engines.

Yet there are, of course, an endless number of fluids that do not follow the Newtonian constitutive laws and an increasing number of these are being handled industrially on a rather large scale. As a consequence, the equipment for moving and processing these fluids requires careful design and analysis for economical operation and this implies the need for a more basic understanding of the flow and heat transfer characteristics of these particular non-Newtonian fluids. Various investigations of non-Newtonian fluids have, of course, been performed over the years and some of this work has been described in books as well as survey papers. (See for example, ref. [1].) Some experiments of this kind were conducted in our laboratories on dilute solutions of polymers, on dispersions of particulates and fibers in water, and on solutions of polymers in kerosene. The work on the first two fluids was stimulated by an interest in applications involving the drag-reducing properties of these fluids; the work on the third was a part of an investigation of anti-misting kerosene, a fuel designed to reduce the danger of explosions in aircraft accidents.

In this paper we report the results obtained with tomato puree. While performing this work we certainly met with considerable scepticism and some ridicule. Yet the preparation of food is without doubt a most basic and important activity, and heat transfer is certainly a crucial part of food preparation or food processing. Tomatoes in particular represent a very important farm product. The value of the yearly California crop is about 400 million dollars, and the value of the products made from the tomatoes—such as ketchup, tomato paste, and tomato soup—is, of course, even much larger than that. It seems very appropriate, therefore, to increase at least somewhat the emphasis on investigations of these more complex common fluids.

It was the purpose of the present work to contribute to this endeavor by providing some basic data on heat transfer and friction coefficients for tomato puree as one of these fluids. Indeed, there has not been much work conducted on the friction and heat transfer characteristics of this type of fluid, and even less that has taken appropriately into account their complex rheological characteristics.

Among the early investigations concerned with the rheological aspects of food materials are the studies by Charm [2, 3] who investigated the viscosity models

NOMENCLATURE

B	Arrhenius constant
c	specific heat
C_F	friction coefficient
C_H	heat transfer coefficient
d	diameter of test pipe
D	diameter of capillary
L	length of pipe
n	exponent of the shear rate
Nu	Nusselt number
Δp	pressure drop
Pr	Prandtl number
Pr_a	apparent Prandtl number
Re	Reynolds number
Re_a	apparent Reynolds number
T	absolute temperature
V	average velocity
x	distance from entrance to pipe.

Greek symbols

$\dot{\gamma}$	shear rate
$\dot{\gamma}_w$	shear rate at the wall
η_a	apparent viscosity
η_{eff}	effective viscosity
ν_a	apparent kinematic viscosity
ν_{eff}	effective kinematic viscosity
ρ	density
τ	shear stress
τ_w	shear stress at the wall.

applicable to these fluids and by Eolkin [4] who proposed the in-line measurement of viscosity at various shear rates for the monitoring of production lines. Power law models, yield stresses, and pseudoplasticity were studied by Harper and El Sahrigi [5] for tomato concentrates, by Saravacos [6] for fruit purees, by Krumel and Sarkar [7] for gum additives, and by Van Vliet and Van Hooijdonk [8] for fruit juices. More recently, viscosity and flow models were investigated by Rao and Anantheswaran [9] and Rao and Cooley [10].

The few heat transfer investigations include those by Charm and Merrill [11] in concentric heat exchangers, by Harper [12] in evaporators, and by Jowitt and McCarthy [13] in plate heat exchangers.

EXPERIMENTAL INSTALLATION

A diagram of the experimental installation is shown in Fig. 1. The arrangement is basically very simple. The central component, the test section, consists of an approximately 5 m long straight circular tube with an inner diameter of 8 mm. Pressure gauges and thermocouples were placed at several stations spaced at intervals of about 0.6 m along the tube. A thermocouple is placed in the fluid just upstream of the entrance to the test section to determine the initial fluid temperature. The fluid from the test section is discharged into a mixing chamber and the mixed mean temperature of the fluid is determined by a thermocouple in this chamber. The test fluid is mixed and conditioned in a supply tank. It is then drawn into a cylinder by a receding piston and next forced through the test section as the piston moves forward. It is a 'once-through' flow arrangement and each batch of fluid is used only once. The piston is driven by an electric motor through a worm gear and pressure is supplied to the back of the piston to assist the motor. The flow rate was derived from the rate of piston displacement.

The wall of the test section itself served as an electric heater for the fluid flowing through the tube. Electric current was passed through the wall and the local power dissipation was calculated from the measured current and voltage drop. Detailed information on the test installation is given in ref. [14].

FLUID PROPERTIES

The test fluid, as pointed out earlier, was tomato puree diluted to a total solid concentration of 6%, the remainder being water. The density (in kg m^{-3}) of the puree diluted to 6% was found to be $\rho = 1110 - 0.307\ T$ (K) between 293 and 313 K. Because of the nature of the fluid, it was assumed in the computations that the heat capacity and the thermal conductivity were equal to that of water. The viscosity, however, had to be determined experimentally. With a non-Newtonian fluid of this type, the viscosity, of course, is no longer a simple concept and its dependence on the shear rate now becomes a major factor.

Various definitions of viscosity for fluids of this type are discussed in detail in the literature, the review by Cho and Hartnett [15] being particularly pertinent for the present application. Only a brief summary, therefore, needs to be given here, outlining the definitions and computational procedures. For the presentation of our data the so-called 'apparent viscosity', η_a, was found to be the most suitable property. This viscosity is defined by the relation

$$\tau_w = \eta_a \dot{\gamma}_w \quad (1)$$

where τ_w is the wall shear stress and $\dot{\gamma}_w$ the shear rate at the wall. In order to determine the apparent viscosity for the test fluids, tests were conducted in a 2 mm diameter capillary tube. The shear stress at the

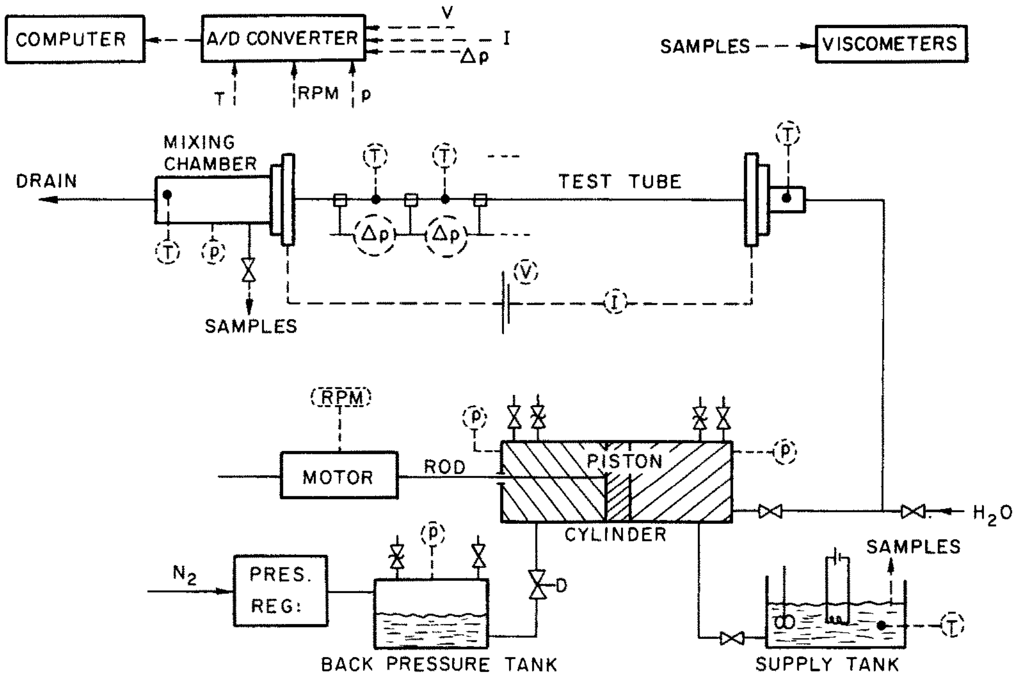

FIG. 1. Schematic of the experimental installation.

wall, τ_w, and the average velocity, V, were computed from the measured head loss and flow rate, respectively. The measurements were repeated for a range of flow rates. The data were expressed in terms of a relation between τ_w and $(8V/D)$ where D is the diameter of the capillary. For a Newtonian fluid $(8V/D)$ is equal to the wall shear rate. For a non-Newtonian fluid this equality no longer holds but the quantity $(8V/D)$ still gives at least a qualitative indication of the wall shear rate. The expression

$$\tau_w \bigg/ \left(\rho \frac{8V}{D}\right) = \nu_{eff} \tag{2}$$

is called here the 'effective' viscosity. In Fig. 2 ν_{eff} is plotted against $(8V/D)$ and the graph illustrates the strong dependence of the viscosity on the shear rate. A quantity 'n' is next derived from the relationship for τ_w by differentiation

$$n = \mathrm{d}[\log(\tau_w)]/\mathrm{d}[\log(8V/D)]. \tag{3}$$

The quantity, n, represents the exponent in the power model representation for a fluid in which the shear stress is assumed to vary with the nth power of the shear rate. The shear rate at the wall may then be computed and equation (1) becomes

$$\tau_w = \eta_a \left[\frac{3n+1}{4n} \frac{8V}{D}\right] \tag{4}$$

from which the *apparent dynamic viscosity* η_a, and the corresponding kinematic viscosity $\nu_a = \eta_a/\rho$ are obtained. On the basis of this viscosity we define the apparent Reynolds number as

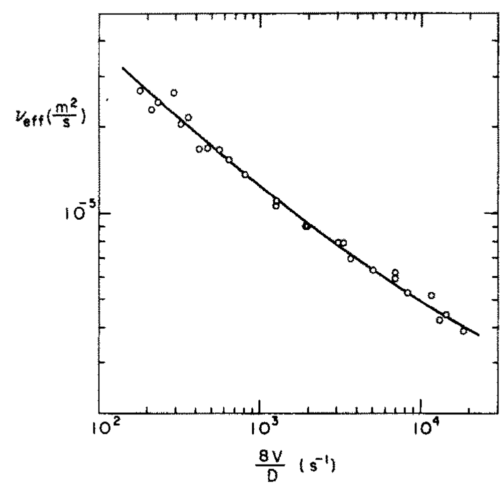

FIG. 2. Effective viscosity of tomato puree (normalized to 25°C).

$$Re_a = \frac{\rho V d}{\eta_a} \tag{5}$$

and the apparent Prandtl number as

$$Pr_a = \frac{c\eta_a}{k}. \tag{6}$$

The determination of η_a was repeated for a number of temperatures between 15 and 45°C. The temperature effect could be expressed adequately at a constant shear rate by the relation

$$\eta(T_1, \dot{\gamma}_0) = \eta(T_0, \dot{\gamma}_0)\, e^{(B/T_1 - B/T_0)}. \tag{7}$$

The Arrhenius coefficient B was obtained from the experiments and was found to be approximately constant throughout the range of shear rates and equal to $B = 2710\ \mathrm{K}^{-1}$.

The results shown in Fig. 2 have already been normalized to 25°C using this relationship.

Viscosity measurements of this kind have been performed by previous authors, and it is reassuring that their data are very comparable to the present results indicating that tomato puree at a given concentration is a relatively reproducible substance. Harper and El Sahrigi [5], for example, reported a viscosity of $17.1 \times 10^{-6}\ \mathrm{m^2\ s^{-1}}$ and $n = 0.59$ for a 5.8% concentration, a shear rate of $500\ \mathrm{s^{-1}}$ and a temperature of 32°C. Whereas our results indicate $16.8 \times 10^{-6}\ \mathrm{m^2\ s^{-1}}$ and $n = 0.62$ at $500\ \mathrm{s^{-1}}$ and 25°C. The temperature dependence found by Harper and El Sahrigi was given by the exponential constant $B = 3080\ \mathrm{K}^{-1}$ which is somewhat larger than the present result, but is still comparable. Other studies such as that by Saravacos [6] indicate Arrhenius coefficients for different purees which are very close to our results.

EXPERIMENTAL ACCURACY

The overall accuracy of the installation may, perhaps, be characterized best by the data obtained for pure water. The friction coefficient was measured over a range of Re from 10^4 to 10^5 and the results were compared with those predicted from various generally accepted equations. Taking the equation originally proposed by Blasius

$$C_F = 0.079 Re^{-0.25} \tag{8}$$

as representative, the present experimental data were within $\pm 1\%$ of those predicted from this equation.

Heat transfer coefficients were measured for a Prandtl number of about 5.5 and the same range of Reynolds number as covered for the friction experiments. The expression

$$Nu = 0.015 Re^{0.83} Pr^{0.5} \tag{9}$$

proposed by Kays [16] was used for comparison. The present data were within 3 and 0% of that relation. The experimental data are bracketed by the values obtained from other well-known correlations such as that by Sleicher and Rouse [17] and Petukhov [18].

The agreement of the present data with those of previous investigations was taken as an indication that the experimental installation would yield results of acceptable accuracy.

The principal additional error introduced in the experiments with the tomato puree has to do with the measurement of the viscosity. The measurements themselves were accurate and repeatable in the given viscosimeter. The size of the fibers, however, may not have been negligible compared to the diameter of the capillary tube. As a consequence there is a possibility that the measurements were influenced somewhat by the size of the tube in the particular viscosimeter. The error, however, is estimated to be less than 10%. As the purpose of this investigation was to provide information on the general behavior of the fluid as well as approximate engineering data, this type of uncertainty is deemed to be acceptable.

A further word of caution is in order in regard to the diameter of the test tube. For complex fluids of the kind considered in this investigation, the combination of the Reynolds number and the Prandtl number, may not be sufficient to describe the heat transfer and friction results. An additional parameter involving the elastic behavior of the fluid may come into play, which could make the results dependent on the pipe diameter. A discussion of this aspect may be found in ref. [19].

EXPERIMENTAL FRICTION COEFFICIENTS

In Fig. 3 the experimentally obtained friction coefficients are shown as a function of the apparent Reynolds number. For comparison the friction coefficient for a Newtonian fluid is also plotted. It is seen that in terms of the present representation the friction coefficient of the tomato puree solution in the turbulent range is below that of the pure Newtonian fluid and the test solution may, therefore, be said to be drag reducing. The apparent Reynolds number, in fact, seems to lend itself particularly well to defining drag reduction which may be explained in the following way. (See also ref. [14].) As usual in turbulent flow the properties at the wall are the most important ones for describing the transport process. The apparent Reynolds number, now, is based on these wall properties, in particular the temperature and the shear stress at the wall. If the friction coefficient, C_F, is plotted as a function of this apparent Reynolds number Re_a, therefore, one might expect a relationship between C_F and Re_a very similar to that obtained for the turbulent flow of a Newtonian fluid. A fluid for which the friction coefficient falls below this line may be called 'drag reducing', and this reduction is usually ascribed to viscoelasticity or a similar mechanism which interferes with the turbulent motion. In this sense the tomato puree was called drag reducing. As an example of a strongly non-Newtonian fluid that is *not* drag reducing, a slurry of 5% bentonite in water may be taken. The data for that fluid [20] are also shown in Fig. 3, and it is seen that the curve closely matches that for a Newtonian fluid. In the laminar range the line defined by the measured friction coefficient is parallel to that for a pure Newtonian fluid, but well above the Newtonian value. The two lines are not expected to coincide, as even a fluid following the power law model exactly would lead to a difference. For the magnitude of the exponent n applicable to the present fluids, this factor, however, accounts for only a part of the difference and the remainder is probably attributable to deviations of the actual velocity profile from that of a simple 'power law' fluid. It should also be noted that the break in the

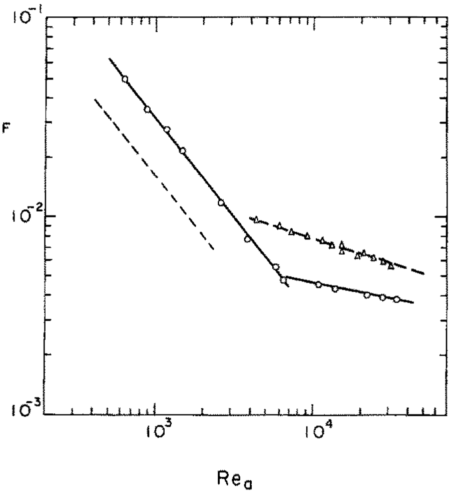

FIG. 3. Friction coefficient vs apparent Reynolds number: O, points for tomato puree; △, points for a 5% bentonite solution, shown for comparison; ---, data for a Newtonian fluid. (The bentonite data closely follow the line for the Newtonian fluid.)

curve indicating transition to turbulent flow occurs at a Reynolds number of approximately 7000 compared to values of about 2000 which are usually quoted for Newtonian fluids.

HEAT TRANSFER RESULTS

The heat transfer results are first presented in Fig. 4 as Nusselt numbers vs the apparent Reynolds number. The experiments cover a range of Pr_a from about 15 to 70 and Pr_a is different for each experimental point. A corresponding line for a Newtonian fluid (taking into account a corresponding variation in Pr_a) is also shown. A reduction in heat transfer coefficient in the turbulent regime is indicated by the comparison of the two curves in the turbulent regime. The data can be generalized somewhat by presenting the Colburn number, $C_H Pr_a^{2/3}$ (which is the same as $Nu/Re_a Pr_a^{1/3}$), as a function of Re_a. The resulting curve is shown in Fig. 5. Just as in Fig. 3, a change in flow regime also seems to be in evidence and for Re_a greater than about 7000 the flow appears to be turbulent. The Colburn factor for a Newtonian fluid in turbulent flow is shown for comparison. The two lines have similar trends, with the one for the tomato puree again showing a certain amount of heat transfer reduction. The Colburn factor for the tomato puree appears to have been reduced by approximately 30% with respect to a Newtonian fluid.

All of the results reported so far were based on measurements taken at a station of the test section sufficiently far downstream ($x/d > 400$) to ensure that the flow was fully developed. In Fig. 6 the changes of Nu are shown vs the distance along the test section to illustrate the entrance effects and the degree to which equilibrium conditions were reached at the measurement stations. Each line in Fig. 6 corresponds to a

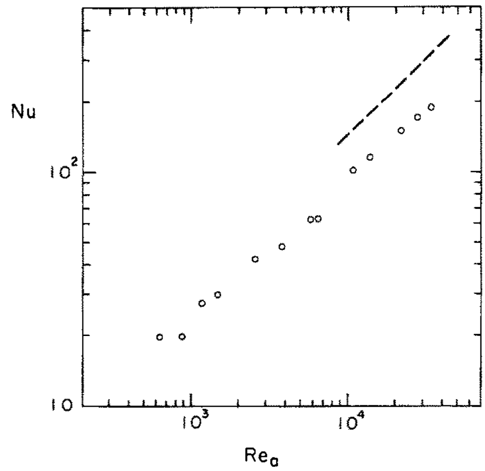

FIG. 4. Nusselt number vs apparent Reynolds number for tomato puree: ---, data for Newtonian fluid.

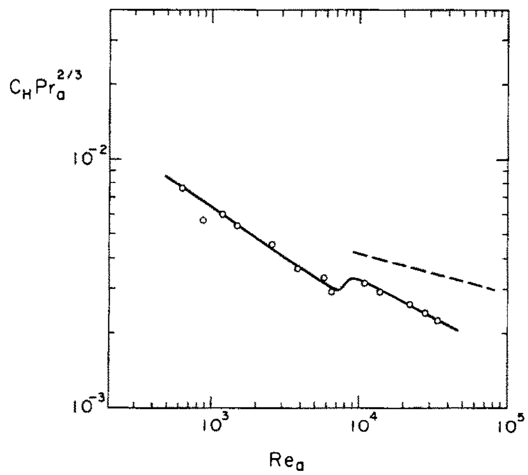

FIG. 5. Colburn number, $C_H\ Pr_a^{2/3}$ vs apparent Reynolds number for tomato puree: ---, data for a Newtonian fluid.

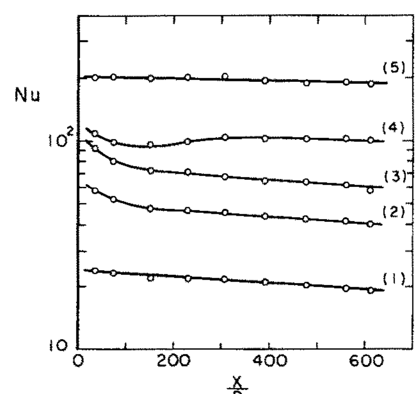

FIG. 6. Nusselt number as a function of distance for tomato puree: curve (1), $Re_a = 880$ ($Pr_a = 61.9$); (2), 2590 (45.8); (3) 5810 (34.1); (4), 10900 (26.2); (5), 33800 (15.4).

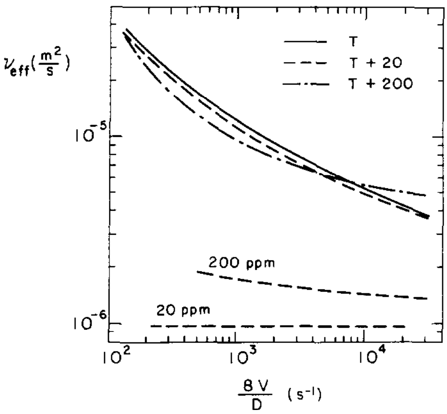

FIG. 7. Effective viscosity of combinations of tomato puree and polymer: T = tomato puree; T+20 and T+200 represent tomato puree with 20 and 200 p.p.m. of polymer, respectively. The curves for solutions of polymer in water are labelled 20 and 200 p.p.m.

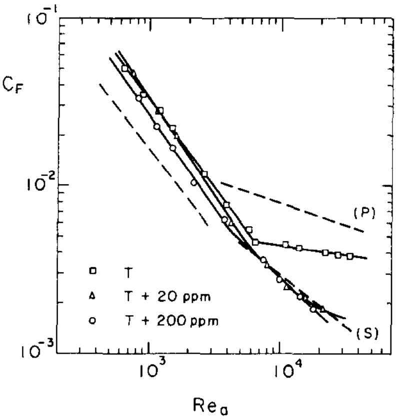

FIG. 8. Comparison of friction results for various combinations of tomato puree and polymer: T = tomato puree; T+20 and T+200 represent tomato puree with 20 and 200 p.p.m. of polymer, respectively. Line (P) represents data for Newtonian fluids; Line (S) represents data for 200 p.p.m. polymer in pure water.

flow of a certain combination of Re_a and Pr_a which was fairly constant all along the tube. Changes in Nu beyond $x/d > 400$ are certainly minor and the measurements taken beyond this distance may well be taken to represent equilibrium conditions. Again, a transition regime appears to take place between $Re_a = 5000$ and 10 000 as indicated here by changes in the shape of the curves.

EFFECT OF POLYMER ADDITIVES

To widen the scope of our information on complex fluids, we also investigated the effect of polymer additives on tomato puree. In previous investigations [14] solutions of polyacrylamide in water were investigated and major reductions in friction and heat transfer coefficients were observed over the coefficients for pure water. In the present study, experiments were conducted with two solutions consisting of tomato puree (as described before) with 20 and 200 p.p.m., of polyacrylamide (AP273) added, respectively.

The first step in the investigation was to determine the viscosities and in Fig. 7 the effective kinematic viscosity is shown as a function of $(8V/D)$. The measurements were carried out in the same way as described earlier. It is seen that the addition of the polymer does not change the effective viscosity of the tomato puree very drastically. The structure of the puree itself seems to be the major factor in determining this property. For comparison the values of the kinematic viscosity for solutions of 200 and 20 p.p.m. of polyacrylamide in pure water are also shown. (The viscosity of the 20 p.p.m. solution, incidentally, is almost equal to that of pure water.) The Arrhenius-type factor for correction of the temperature effect was found to be $B = 2070\ K^{-1}$ for modified purees.

The experimentally-obtained friction coefficients are shown in Fig. 8. The curve for the tomato puree without additives is the same as that in Fig. 3. The additives clearly lead to a drag reduction in the turbulent flow range and it is interesting to note that the effect of the 20 p.p.m. addition is about equivalent to that of the 200 p.p.m. addition. Furthermore, the experimental curve for a 200 p.p.m. solution in pure water is shown by a dashed line and it is quite interesting to note that it coincides almost exactly with the data of the puree solutions with polymer additives. It should be pointed out that the data for all three of the polymer solutions fall close to the friction 'asymptote' defined by Virk [21]. Virk postulated that the friction coefficient could not be reduced below this asymptote. The present data show that the three solutions reduce friction by almost the maximum amount predicted. (The asymptote is not shown separately as it is so close to the other lines.)

One should recall at this point that the representation in Fig. 8 depends on the definition of the apparent Reynolds number. The viscosities of the 200 p.p.m. solution in the tomato puree and in pure water are very different as can be seen from Fig. 7. It is through the use of Re_a that the friction results appear to be so similar. This may be taken as a further indication that the parameter Re_a is a meaningful one for the types of fluids discussed. In this instance it may properly scale the interaction of the polymer with the turbulence near the wall. This conclusion also implies that the apparent Reynolds number was based on acceptable measurements, which in turn may be taken as an indication that the apparent viscosity, ν_a, was indeed measured with good accuracy.

The heat transfer results are shown in Fig. 9, in terms of the Colburn number, $C_H\, Pr_a^{2/3}$. The fluid with 20 p.p.m. of polymer and the one with 200 p.p.m. of polymer define two separate curves. In addition, the curves for pure tomato, pure water and for a 200 p.p.m. pure water solution are shown for reference. It is seen that the addition of the polymers decreases the heat transfer coefficient very significantly below the

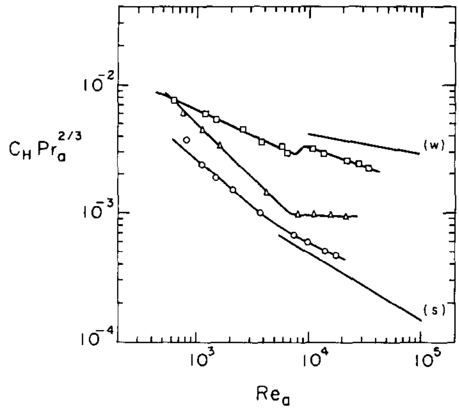

FIG. 9. Heat transfer results for various combinations of tomato puree and polymer: T = tomato puree (□); T+20 (△) and T+200 (○) = tomato puree with 20 and 200 p.p.m., respectively. Curve (w) represents data for pure water, and curve (s) for a solution of 200 p.p.m. in pure water.

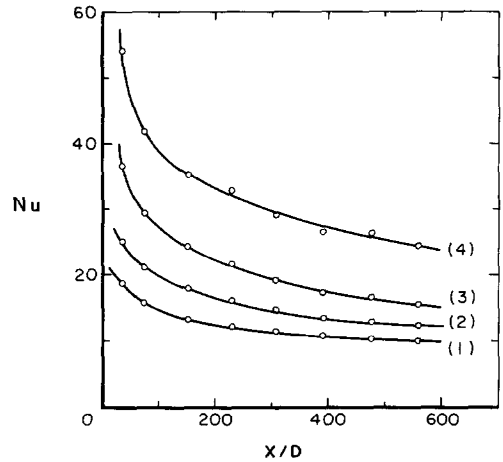

FIG. 10. Heat transfer as a function of distance for tomato puree with 200 p.p.m. of polymer: curve (1), $Re_a = 1130$ ($Pr_a = 54.2$); (2), 3680 (38.8); (3), 7380 (31.3); (4), 17670 (27.6). (Wall temperature reference; 6% + 200 p.p.m.)

values obtained for the solution without additives. These data in turn were below those for pure water. Incidentally, the data for the fluids containing 200 p.p.m. of polymer are very close to the values predicted by the heat transfer asymptote. This asymptote is defined by Cho and Hartnett [15] in a manner analogous to that for the friction asymptote.

The effect of x/d on heat transfer may also be of interest and Nu is shown as a function of Re_a in Fig. 10 for the tomato puree containing 200 p.p.m. of the polymer additive. The curves emphasize the fact that Nu depends strongly on x/d. Many heat exchanger tubes will have lengths of less than $x/d = 300$ and the average Nusselt number for these cases will be significantly higher than the equilibrium value.

SUMMARY AND CONCLUSIONS

There are many complex fluids which are processed commercially or industrially on a rather large scale and the behavior of many of these fluids cannot be adequately described in terms of a Newtonian fluid. Relatively little research effort has been devoted to gain an understanding of the behavior of such fluids in the past, but it now seems very appropriate to place more emphasis on a systematic investigation of some of the characteristics of these fluids. In this context we have selected tomato puree, which is handled in large quantities in the food industry, and we have attempted to provide information on the heat transfer and friction coefficients for forced convection in a tube. This is the kind of information that is essential for many engineering designs and which by now is almost taken for granted for Newtonian fluids. The present data, hopefully, will contribute to the fund of information on less well-behaved fluids.

Although individual data points may be of some interest in themselves, a generalized presentation in terms of relevant parameters is much more valuable. It was possible to provide such a presentation by means of the apparent Reynolds number, Re_a. The crucial quantity required for the computation of this parameter is the apparent viscosity, and the effect of shear stress on this viscosity had to be determined with great care. An apparent Prandtl number was defined in an analogous way.

The heat transfer and friction coefficients were presented as a function of Re_a and Pr_a, and show that tomato puree without additives may exhibit a significant drag-reducing behavior in the turbulent regime, but an increase in heat transfer coefficient in the laminar regime. The data were obtained with a single tube of a given size and adjustments for the diameter effect may still have to be applied. Nevertheless, the data may serve as a guide for the design of heat exchange equipment for certain restricted applications. In a more general way it is hoped that the results will alert the designer to the kind of similarities and differences that may be expected for a fluid like the tomato puree as compared to pure water.

The results obtained with the polymer additives give an indication that small additions of such substances might reduce even more the turbulent friction and heat transfer characteristics of the fluids below Newtonian values. The polymers added in the present experiments were somewhat artifical ones. There are, however, regular food additives or even natural foodstuffs which have similar drag-reducing effects and it is important for the designer to be aware of the rather significant changes that can result from such ingredients. Furthermore, the results possibly may be extrapolated to obtain a qualitative assessment of heat transfer and friction coefficients for a variety of fruit sauces and fruit purees. In each case, of course, the apparent viscosity would first have to be determined. We hope that the information presented will be of some use to engineers designing equipment for the kind of fluids that we have investigated. Perhaps more importantly, we also hope to have provided a framework for presenting data for such fluids, and to have encouraged other investigators to devote some of their efforts to such messy yet nourishing fluids.

Acknowledgments—The authors wish to thank Mr J. F. Cullen and the Carnation Co. for their interest in our work and for supplying the test fluid. We also wish to express our appreciation to the Jet Propulsion Laboratory for their support and especially to Dr V. Sarohia for his help and assistance in carrying out our project. We also want to thank Mr H. Ahn for his conscientious assistance in conducting the experiments.

REFERENCES

1. R. I. Tanner, *Engineering Rheology*. Oxford University Press, London (1985).
2. S. E. Charm, Viscometry of non-Newtonian food materials, *Fd Res.* **25,** 351–362 (1960).
3. S. E. Charm, The nature and role of fluid consistence in food engineering applications. In *Advances in Food Research*, pp. 355–435. Academic Press, New York (1962).
4. D. Eolkin, The plastometer, a new development in continuous recording and controlling consistometers, *Fd Technol.* 253–257 (May 1957).
5. J. C. Harper and A. F. El Sahrigi, Viscometric behavior of tomato concentrates, *J. Fd Sci.* **30**(3), 470–476 (1965).
6. G. D. Saravacos, Effect of temperature on viscosity of fruit juices and purees, *J. Fd Sci.* **35,** 122–125 (1970).
7. K. L. Krumel and N. Sarkar, Flow properties of gums useful to the food industry, *Fd Technol.* 36–44 (April 1975).
8. T. Van Vliet and A. C. Van Hooijdonk, The gel properties of some beverages. In *Advances in Rheology* (Edited by B. Mena, A. Garcia-Rejon and C. Rangel-Nafaile), Vol. 4, pp. 115–122. Universidad Nacional Autonoma de Mexico, Mexico (1984).
9. M. A. Rao and R. C. Anantheswaran, Rheology of fluids in food processing, *Fd Technol.* 116–126 (February 1982).
10. M. A. Rao and H. J. Cooley, Applicability of flow models with yield for tomato concentrates, *J. Fd Process Engng* **6,** 159–173 (1983).
11. S. E. Charm and E. W. Merrill, Heat transfer coefficients in straight tubes for pseudoplastic food materials in streamline flow, *Fd Res.* **24,** 319–331 (1959).
12. J. C. Harper, Viscometric behavior in relation to evaporation of fruit purees, *Fd Technol.* 557–561 (November 1960).
13. R. Jowitt and O. J. McCarthy, The experimental determination of laminar flow heat transfer coefficients for Newtonian and non-Newtonian food liquids in tubular and plate exchangers, *Proc. 4th Int. Congress Food Sci. and Technol.*, Madrid, Vol. 4, pp. 350–360 (1974).
14. E. F. Matthys, An experimental study of convective heat transfer, friction, and rheology for non-Newtonian fluids: polymer solutions, suspensions of fibers, and suspensions of particulates, Ph.D. thesis, California Institute of Technology, Pasadena, California (1985).
15. Y. I. Cho and J. P. Hartnett, Non-Newtonian fluids in circular pipe flow. In *Advances in Heat Transfer*, Vol. 15, pp. 59–142. Academic Press, New York (1982).
16. W. M. Kays, *Convective Heat and Mass Transfer*. McGraw-Hill, New York (1966).
17. C. A. Sleicher and M. W. Rouse, A convenient correlation for heat transfer to constant and variable property fluids in turbulent pipe flow, *Int. J. Heat Mass Transfer* **18,** 677–683 (1975).
18. B. S. Petukhov, Heat transfer and friction in turbulent pipe flow with variable physical properties, *Adv. Heat Transfer* **6,** 503–564 (1970).
19. E. F. Matthys and R. H. Sabersky, A method of predicting the 'diameter effect' for heat transfer and friction of drag-reducing fluids, *Int. J. Heat Mass Transfer* **25,** 1343–1351 (1982).
20. E. F. Matthys, H. Ahn and R. H. Sabersky, Friction and heat transfer measurements for clay suspension with polymer additives, *J. Fluids Engng* **109,** 307–312 (1987).
21. P. S. Virk, Drag reduction fundamentals, *A.I.Ch.E. Jl* **21**(4), 625–656 (1975).

COEFFICIENTS DE TRANSFERT DE CHALEUR ET DE FROTTEMENT POUR LA PUREE DE TOMATE

Résumé—Il y a un manque de données concernant les fluides traités en grande quantité et qui ne suivent pas la loi des fluides newtoniens. La purée de tomate est un de ces fluides et on le choisit dans cette étude. Les coefficients de transfert thermique et de frottement sont obtenus pour un domaine couvrant les conditions usuelles et il est possible de présenter les résultats en définissant une viscosité apparente pour calculer des nombres de Reynolds et de Prandtl. La viscosité apparente dépend du taux de cisaillement et cet effet est pris en compte. Des expériences supplémentaires sont conduites avec de la purée de tomate contenant des petites quantités d'additifs polymères. Les données expérimentales sont comparées avec celles des fluides newtoniens. Ces résultats peuvent fournir un guide à l'ingénieur confronté à la conception d'un échangeur de chaleur pour les fluides fibreux complexes tels que la purée de tomate.

WÄRMEÜBERGANGS- UND REIBUNGSKOEFFIZIENTEN FÜR TOMATEN-PÜREE

Zusammenfassung—Es besteht vermutlich ein Interesse an technischen Daten über Fluide, die in großen Mengen hergestellt werden, sich jedoch nicht wie newton'sche Fluide verhalten. Tomaten-Püree wurde als Vertreter derartiger Fluide in der vorliegenden Arbeit untersucht. Es wurden Wärmeübergangs- und Reibungskoeffizienten für bestimmte Versuchsbedingungen ermittelt, die in der üblichen Form dargestellt werden konnten: durch Einführen einer scheinbaren Viskosität und durch Berechnen einer Reynolds-Zahl und einer Prandtl-Zahl in Abhängigkeit dieser scheinbaren Viskosität. Die Abhängigkeit der Schein-Viskosität von der Schergeschwindigkeit wurde dabei berücksichtigt. Es wurden zusätzlich Experimente durchgeführt mit Tomaten-Püree, das geringe Polymer-Zusätze enthielt. Die experimentell ermittelten Wärmeübergangs- und Reibungskoeffizienten wurden mit denen newton'scher Fluide verglichen. Es bleibt zu hoffen, daß die Ergebnisse für die Auslegung von Wärmeaustauschern für komplexe, faserige Fluide—wie z. B. Tomaten-Püree—nützlich sind.

КОЭФФИЦИЕНТЫ ТЕПЛОПЕРЕНОСА И ТРЕНИЯ ПРИ ИЗГОТОВЛЕНИИ ТОМАТНОГО ПЮРЕ

Аннотация—В настоящее время имеется настоятельная необходимость в накоплении данных о технических характеристиках сред, которые не подчиняются законам ньютоновских жидкостей и изготавливаются в больших количествах. Одной из таких сред является томатное пюре. Оно и явилось объектом данного исследования. Определены коэффициенты теплообмена и трения для диапазона рабочих условий. Результаты представлены в обычном виде с использованием кажущейся вязкости и чисел Рейнольдса и Прандтля, построенных на этой вязкости. Вязкость зависит от напряжения сдвига, что учитывалось при расчетах. Дополнительные эксперименты были проведены с томатным пюре, содержащем небольшие полимерные добавки. Измеренные коэффициенты теплопереноса и трения сравнивались со значениями для ньютоновских жидкостей. Вполне возможно, что результаты работы окажутся полезными при проектировании теплообменного оборудования для таких сложных волокнистых сред, какой является томатное пюре.