A C T A   A L I M E N T A R I A   P O L O N I C A
Vol. XIII (XXXVII), No. 3 1987

Z. KEMBŁOWSKI

INVESTMENT COSTS AND ENERGY SAVING METHODS OF TRANSPORTATION OF FOOD PRODUCTS IN PIPES

Institute of Chemical Engineering, Technical University, Łódź

The paper is concerned with the transportation in pipes of substances exibiting complex rheological behaviour. A short review of methods of transportation — with may be of interest to various branches of food industry — is presented.

INTRODUCTION

Many substances transported in pipes in the food industry exhibit a complex rheological behaviour. Therefore, the principles and some recent achievements of non-Newtonian fluid mechanics should be taken into account in designing and performing of pumping operations. As one knows the situation in the food industry is far from being satisfactory from this point of view. The paper presents a short review of some of the methods of transportation of non-Newtonian fluids in pipes which may be of interest to various branches of the above mentioned industry.

THE PROPER CHOICE OF PROCES PARAMETERS IN A PUMPING OPERATION

Fluids with a pronounced non-Newtonian behaviour usually have so high viscosities that in almost all of industrially interesting situations their flow is laminar. On the other hand the majority of non-Newtonian fluids processed in the food industry belong to the category of shear-thinning substances, i.e. the non-Newtonian, shear-dependent viscosity of these materials decreases with the increase of shear rate.

For the sake of simplicity let us consider a purely viscous non-Newtonian fluid without a yield stress. The simplest rheological model of such a substance is the well known power law of Ostwald-de Waele

$$\tau = k\dot{\gamma}^{n} \tag{1}$$

where τ is the shear stress, $\dot{\eta}$ — shear rate, and k, n — rheological parameters of the model. For shear-thinning fluids $n < 1$.

Taking into account the general equation for laminar flow of a purely viscous fluid in a cylindrical tube (derived under the assumption of no slip at the tubes wall)

$$\frac{Q}{\pi R^3} = \frac{1}{\tau_w^3} \int_0^{\tau_w} \tau^2 f(\tau) \, d\tau \tag{2}$$

and introducing the dependence for power-law fluids

$$f(\tau) = \left(-\frac{du}{dr}\right) = \left(\frac{\tau}{k}\right)^{\frac{1}{n}} \tag{3}$$

one obtains after integration and simple rearrangement a generalization of the familiar Hagen-Poiseuille equation of the following form

$$Q = \frac{n\pi R^3}{3n+1} \left(\frac{R\Delta p}{2Lk}\right)^{\frac{1}{n}} \tag{4}$$

In Eqs. (2), (3) and (4) Q refers to the volumetric flow rate, τ_w — shear stress at the tube wall, Δp — pressure drop due to friction, R — tube radius, and L — tube length.

Writing Eq. (4) in the form

$$p\Delta = \frac{2k}{\pi^n} \left(\frac{3n+1}{n}\right)^n \frac{LQ^n}{R^{3n+1}} \tag{5}$$

one may draw interesting conclusion of practical importance. For Newtonian fluids the rheological parameter $n = 1$ and — as one knows — the pressure drop ΔP is proportional to the volumetric flow rate Q and it is inversely proportional to the tube radius to the fourth power/which means that even a small increase in pipe diameter is very effective in reducing pressure drop). For a highly shear-thinning fluid, however, for which the rheological parameter n is close to zero, the situation is quite different. The pressure drop is then proportional not to $\frac{1}{R^4}$, but to a value close to $\frac{1}{R}$, and it is almost completely insensitive to the flow rate because Δp is propotional to Q^n, which is close to unity.

The second point is illustrated in Fig. 1 where our own experimental data/published in 1967/are presented [8]. In the graph the dependence of the pressure drop due to friction on mean linear velocity, during the flow in a test tube of fibre suspensions of various concentration, is shown. For the suspension of highest concentration, when the rheological parameter n is of the order of 0.1, the line $\Delta p = f(v)$ is almost horizontal.

The important conclusion is that there is no point in building pipelines

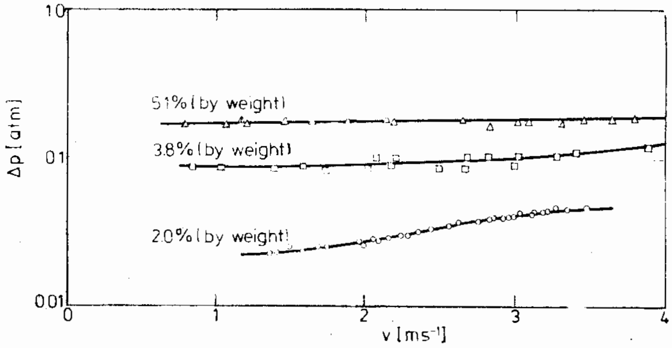

Fig. 1. Experimental data concerning pressure drop due to friction as a function of mean linear velocity for aqueous fibre suspensions of bleached non-beated sulphite pulp of various concentration; the dimensions of the test tube: inner diameter 60 min and length of the test section 2400 mm [8]

of large diameter for pumping highly shear-thinning fluids. This is often done, however, because the designers of pipelines are afraid that for a very viscous non-Newtonian fluid the pressure drop at high velocities will be enormous, and actually there is a neglegible gain of the extra investment costs. Hence, one should pump shear-thinning substances at high flow rates through pipelines of small cross-section because it does not influence the pressure drop very much.

PUMPING OF THIXOTROPIC FLUIDS

Thixotropy is defined as an inelastic, time-dependent behaviour resulting from reversible changes in fluid structure, and is exhibited by many substances processed in the food industry. In the case of thixotropic fluids it is possible to modify their rheological properties in order to obtain desirable behaviour in industrial processing. The modification of rheological properties may be performed using such methods as vibration or high-speed agitation, which lead to a breakdown of the material structure.

As an example of such a procedure one may present a method of transportation of undiluted carbonatation mud in the sugar industry. The method was worked out in the Institute of Chemical Engineering, Łódź Technical University and has been applied in some of the Polish sugar factories [5, 6].

Carbonatation mud is one of the burdensome by-products obtained in sugar factories during purification of raw juice by the carbonatation process. A commonly used method of transportation of carbonatation mud is based upon dilution by water in propotion 1 : 1 and then pumping to settling reservoirs outside the factory. This method has the following disadvantages:

a) Large amounts of sewers are formed, which penetrate to the natural water reservoirs and cause a serious water pollution.

b) One has to build large settling and accumulation reservoirs.

c) The diluted carbonatation mud fermentates quickly, causing a serious air pollution because of fetid exhalations.

d) The diluted carbonatation mud cannot be directly utilized for agricultural purposes or as a row material in lime utilization.

All these disadvantages can be avoided if an undiluted carbonatation mud is transported. But the mud has a solid-like consistency and cannot be transported in this form in pipes. Hence it was necessary to modify somehow the rheological properties of the mud.

The investigations performed by us have shown that undiluted carbonatation mud is a thixotropic substance. In order to take advantage of this fact an apparatus, shown in Fig. 2, was designed and built. The apparatus consists of:

— helical conveyor (1) which transports the mud from the rotary drum filters,

— chute (2),

— desintegrating mill (3) of own construction fitted with an inner pump (4),

— centrifugal pump (5) which pumps tre desintegrated mud through pipeline (6) to the reservoirs outside the factory.

The desintegrating mill (3) is a high-speed agitator of 600 r.p.m. with 30 blades on the shaft arranged along a screw-line. It causes a break-

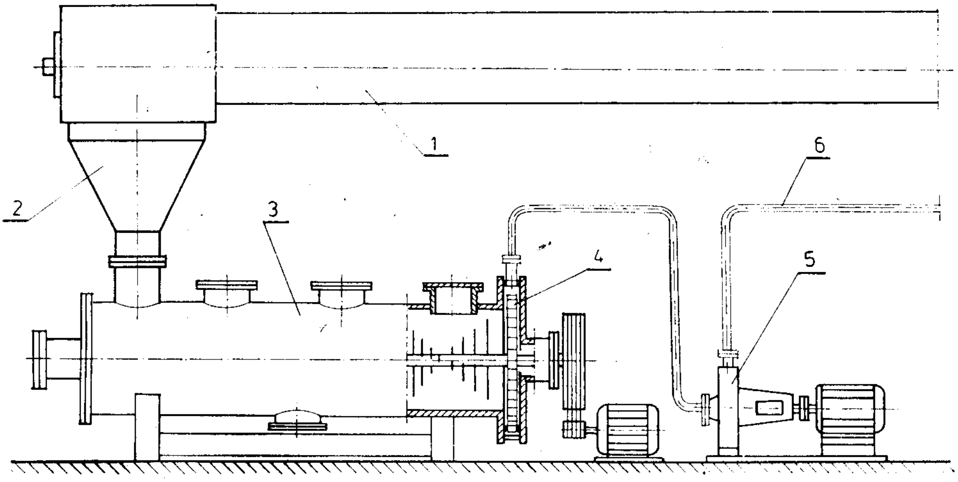

Fig. 2. Diagram of apparatus for transportation of undiluted carbonatation mud: 1 — helical conveyor, 2 — chute, 3 — desintegratin mill, 4 — inner pump, 5 — centrifugal pump, 6 — pipeline

down of the mud structure to such an extent that the mud gains a fluid-like consistency and can be pumped by centrifugal pumps. The mud regains its previous consistency in reservoir and can be utilized almost immediately as a fertilizer or for lime regeneration.

DRAG REDUCTION

The methods of transportation of non-Newtonian fluids discussed until now are of importance rather from the point of view of investment costs or result from technological considerations. Let us turn now to the so called drag reduction methods, i.e. methods which may cause a decrease of pressure drop due to friction in the pipeline and therefore lead sometimes to a reduction of pumping costs because of lower power consumption. Two such methods are presented below.

DRAG REDUCTION BY GAS INJECTION FOR HIGHLY SHEAR-THINNING FLUIDS

In 1954 Ward and Dallavalle [9] have observed for the first time that if a gas (usually air) is injected into a highly shear-thinning liquid or slurry flowing through a pipe, at certain conditions a reduction of the average axial pressure gradient occurs. This apparent hydrodynamic paradox is possible only if the flow is laminar prior to the gas injection, and the volumetric flow rate of gas is such that the two-phase cocurrent flow of gas-liquid mixture has the flow patterns referred to as elongated bubble flow (called also plug flow) or slug flow.

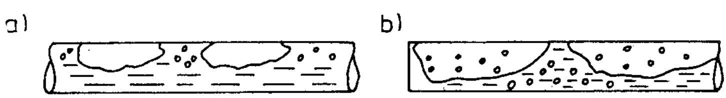

Fig. 3. Two types of flow patterna in two-phase cocurrent gas-liquid flow in a horizontal pipe: a — elongated bubble flow, b — sug flow

The above mentioned two flow patterns are presented schematically in Fig. 3. In the elongated bubble flow large bullet-shaped bubbles occupying most of the pipe cross-section occur. In the slug flow frothy slugs of liquid phase carrying entrained gas bubbles alternate with gas slugs surrounded by liquid films. Of course the described flow patterns are only two of many possible (depending on the velocity of gas and liquid phase, and the physical properties of both phases).

In Fig. 4 a typical example of the drug reduction phenomenon in two-phase flow is shown [2]. The experimental data are presented in the coordinate system: drag ratio Φ_L^2 vs. superficial gas velocity v_{SG}. The drag ratio, as defined by Lockhart and Martinelli [7], is a ratio of the pressure

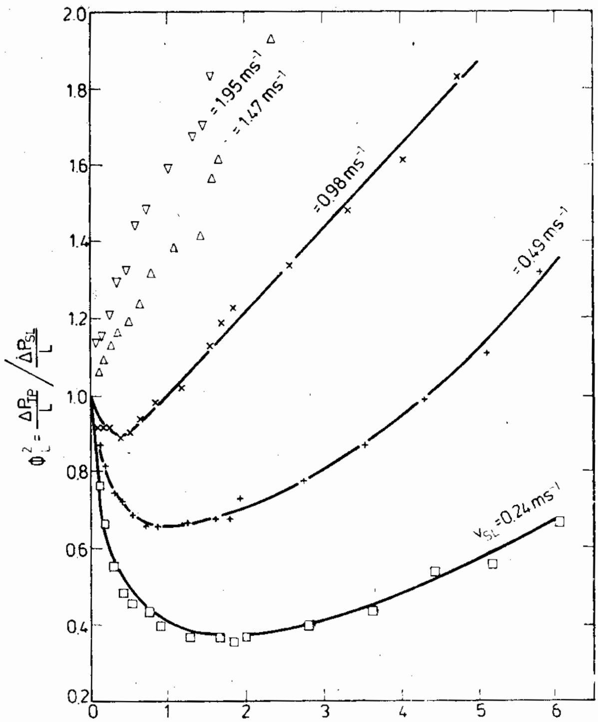

Fig. 4. Drag ratio for the cocurrent flow of air and 24.4% (by vol.) aqueous kaolin suspension in a 42 mm diameter horizontal pipe/according to Chhabra Richardson [2]

drop due to friction in two-phase flow per unit length of the pipe, to the pressure drop in the case of liquid flow alone (at the same flow rate as in two-phase flow) per unit lenghth of the pipe

$$\Phi_L^2 = \frac{\dfrac{\Delta P_{TP}}{L}}{\dfrac{\Delta P_{SL}}{L}} \tag{6}$$

Superficial velocity is the velocity which would occur in the case of flow of only one phase (at the same flow rate as in two-phase flow) through the pipe.

The family of curves presented in Fig. 4 shows the dependence $\Phi_L^2 = f(v_{SG})$ for various values of the superficial liquid velocity v_{SL}. It follows from Fig. 4 that

— in certain range of the superficial liquid velocity the drag ratio falls below unity, i.e. drag reduction occurs,

— the lower the superficial liquid velocity the higher is the drag reduction,

— the curves characterizing the drag reduction pass through a minimum at a certain superficial gas velocity,

— when the superficial liquid velocity reaches high enough values, so that transition to turbulent flow occurs, there is no drag reduction (Φ_L^2 is above unity in the whole range of v_{SG}).

Comparing the drag reduction phenomenon for various shear-thinning liquids one finds that the higher are the shear-thinning properties of the liquid the higher is the drag reduction effect. The maximum reduction of the pressure gradient in two-phase flow in comparison with the flow of liquid phase only may be of the order of 70-80%.

The drag reduction phenomenon may be explained in the following way [4]:

— On one hand the injection of gas into the flowing liquid increases the liquid velocity, and therefore also the pressure gradient. Because of the shear-thinning properties of the liquid, however, the increase may be quite small in laminar flow (it would not be the case in turbulent flow, when the pressure drop due to friction increases with the flow velocity approximately to the second power).

— On the other hand the injection of gas reduces the wetted area of the pipe surface in elongated bubble and slug flow, and the pressure gradient in part of the pipe occupied by gas is so small that it may be neglected.

As a net result of the two opposing effects drag reduction occurs in a certain range of flow parameters.

As far as the savings in power consumption — during the flow of two-phase system exhibiting drag reduction — are concerned it is a complex question. There occurs reduction of power required by the liquid pump, but the air has to be compressed before injection into the pipeline. According to Dziubiński and Richardson [3] savings in power consumption are possible only, if

— the efficiency of the air compressor exceeds that of the pump

— the value of the rheological parameter n of the (power-law) liquid is below 0.5.

DRAG REDUCTION IN TURBULENT FLOW (TOMS PHENOMENON)

Finally, a short note should be devoted to the drag reduction in turbulent flow, called Toms phenomenon. If a tiny amount of high-molecular-weight soluble polymer is added to a Newtonian fluid in turbulent flow through a pipe, a dramatic reduction of pressure drop may occur. The Toms phenomenon is usually presented in terms of the friction factor as a function of Reynolds number. The amount by which the friction factor is lowered is a measure of drag reduction.

In Fig. 5 the Fanning friction factor for water with and without a small amount of poly (ethylene oxide) of weight-average molecular weight $M_w = 6.1 \cdot 10^6$ is shown [1]. It follows from this diagram that for example addition of only 5 ppm of poly (ethylene oxide) to water gives a 40% reduction in friction factor at $Re = 1.0 \cdot 10^5$, while the viscosity of the solution is ca 1% greater than the viscosity of water alone.

The maximum drag reduction which may be achieved in turbulent flow is of the order of 80%. It is worth-mentioning that the Toms phenomenon depends on pipe diameter (the higher the diameter the lower is the drag reduction). An often occurring drawback of this phenomenon is the decrease of the drag reduction in time, caused by the polymer degradation, which may be a problem in long pipelines.

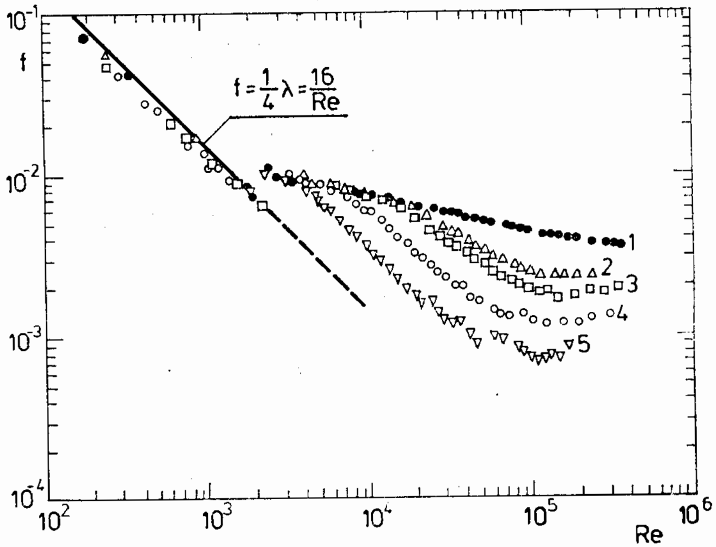

Fig. 5. The dependence of Fanning friction factor on Reynolds number for dilute aqueous solutions of poly (ethylene oxide) of weight-average molecular weight $M_w = 6.1 \times 10^6$; polymer concentration (ppm): 1 — pure water, 2—5, 3—20, 4—100, 5—450 (according to bird, Armstrong and Hassager [1]

The mechanism of drag reduction in turbulent flow is still a matter of controversy. The most probable explanation is that the presence of long polymer chains in the solvent causes a suppression of the small scale turbulence, which is mainly responsible for energy dissipation. In this aspect the elastic properties of the polymer chains are of paramount importance.

From the point of view of food industry the application of Toms phenomenon is rather limited because in most cases the polymer additives would be unacceptable in the transported liquid. It may be, however, of interest in the case of low-viscosity waste liquids pumped out of the factory, especially if the pipelines are very long indeed.

Notation

f — fanning friction factor,
k — rheological parameter in the power law (1), $Pa \cdot s^n$
L — pipe length, m
n — rheological parameter in the power law (1),
Δp — pressure drop due to friction, Pa
ΔP_{SL} — pressure drop due to friction in single-phase liquid flow, Pa
ΔP_{TP} — pressure drop due to friction in two-phase flow, Pa
Q — volumetric flow rate, m^3s^{-1}
R — pipe radius, m
u — local axial velocity, ms^{-1}
v — mean linear velocity, ms^{-1}
v_{SG} — superficial gas velocity, ms^{-1}
v_{SL} — superficial liquid velocity, ms^{-1}
γ — shear rate, s^{-1}
λ — friction factor defined in the Darcy-Weisbach equation,
τ — shear stress, Pa
τ_w — shear stress at the tube wall, Pa
Φ_L^2 — drag ratio defined by eq. 6

LITERATURE

1. Bird R. B., Armstrong R. C., Hassager O.: Dynamics of Polymeric Liquids. John Wiley and Sons, New York 1977, **1**, 113.
2. Chhabra R. P., Richardson J. F.: Cocurrent Horizontal and Vertical Upwards Flow of Gas and non-Newtonian Liquid. Dept. of Chem. Eng., Univ. College, Swansea U.K., 1984, 19.
3. Dziubiński M., Richardson J. F.: J. Pipelines 1985, **5**, 107.
4. Farooqui S. I., Heywood N. I., Richardson J. F.: Trans. I. Chem. E. 1980, **50**, 16.
5. Kembłowski Z., Dziubiński M., Sęk J.: Gaz. Cukrown., 1975, **83** (4), 86.
6. Kembłowski Z., Dziubiński M., Sęk J.: Gaz. Cukrown., 1978, **86** (6), 123.
7. Lockhart R. W., Martinelli R. C.: Chem. Eng. Prog., 1949, **45**, 39.
8. Serwiński M., Kembłowski Z., Kiełbasa J., Iciek J.: Chem. Stos., 1967, **4**, **4B**, 385.
9. Ward H. C., Dallavalle J. M.: Chem. Eng. Prog. Symp. Series 1954, **50/10**, 1.

Author address: 90-924 Łódź, Wólczańska 175

Z. Kembłowski

KOSZTY INWESTYCYJNE I METODY OSZCZĘDZANIA ENERGII W TRANSPORCIE RUROWYM PRODUKTÓW SPOŻYWCZYCH

Instytut Inżynierii Chemicznej, Politechnika, Łódź

Streszczenie

Materiały transportowane w przewodach rurowych w przemyśle spożywczym wykazują złożone cechy reologiczne. W projektowaniu i realizacji transportu ruro-

wego należy wykorzystać podstawy i ostatnie osiągnięcia w mechanice cieczy nienewtonowskich.

W przeciwieństwie do cieczy newtonowskich, ciecze nienewtonowskie wykazują zmniejszenie lepkości ze wzrostem szybkości ścinania można w sposób ekonomiczniejszy przepompować przez przewody surowe o małej średnicy (przy założeniu, że przepływ jest laminarny) i przy dużych prędkościach przepływu. W przypadku materiałów zbliżonych do ciał stałych, których cechy wykluczają użycie do przetłaczania pomp odśrodkowych jest czasami możliwość modyfikacji ich cech reologicznych przez wykorzystanie ich właściwości triksodropowych. Stosując wibrację lub intensywne mieszanie prowadzące do zniszczenia ich struktury można przekształcić je w ten sposób w materiały zbliżone do cieczy, a więc łatwe do przepompowania.

Jeżeli chodzi o zużycie energii podczas przepompowywania to wymienić można dwie następujące, najważniejsze metody zmniejszania oporu:

1. W przypadku płynów wykazujących zmniejszenie lepkości przy wzroście szybkości ścinania wstrzyknięcie powietrza do przewodu może powodować znaczną redukcję gradientu ciśnienia w porównaniu z samym płynem przepływającym przy tej samej prędkości. Efekt ten obserwujemy w przypadku przepływów: osiowego, pęcherzykowego i przepływu rzutowego, jeżeli ciecz lub zawiesina wykazuje przepływ laminarny przed wstrzyknięciem powietrza.

2. W przypadku cieczy o niskiej lepkości wykazujących przepływ turbulentny można wykorzystać tzw. efekt Tomsa. Dodając niewielkie ilości wysokocząstkowego polimeru rozpuszczalnego do transportowanej cieczy jest możliwe w niektórych przypadkach uzyskać spektakularną redukcję oporu. Może to być interesujące dla przemysłu w przypadku pompowania ścieków z zakładu, głównie przez bardzo długie rury.