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OPTIMUM ENERGY CONSUMPTION IN TWO-PHASE TRANSPORT OF AIR AND UNDILUTED CARBONATATION MUD IN SUGAR FACTORY

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A simple flow model of two-phase flow of non-Newtonian thixotropic fluid/gas mixture and a method for evaluating the power saving achieved by injecting air into undiluted carbonatation mud flowing in a horizontal pipe are presented.

INTRODUCTION

The simultaneous flow of gas and liquid in pipes is of a considerable industrial importance. Examples of such flows include air-lift pumps, transportation of liquid/gas mixture in pipes, oil drilling, nuclear processes, food and biotechnology processing etc. In the case of pipe flow a lot of research is currently done on the problem of drag reduction which occurs at a certain condition of two-phase flow of non-Newtonian liquid. As one knows, injection of gas to shear thinning liquid flowing in a pipe may result in a significant reduction in the axial pressure gradient. This occurs at slug flow regimes, provided that the liquid is in laminar flow prior to air injection [34].

The results of research on two-phase flow of non-Newtonian liquid and gas obtained in our laboratory have been used to solve a practical problem of saving energy in transportation of undiluted carbonatation mud in a sugar factory.

A method commonly used in Poland for transportation of carbonatation mud — a burdensome by-product obtained in sugar factory — is based upon dilution by water in proportion 1:1 and pumping to settling reservoirs outside the factory. This method has the following disadvantages: large amounts of burdensome sewers and serious water and air pollution. All these disadvantages can be avoided if an undiluted carbonatation mud is transported.

In our previous investigations we worked out a model describing a rheological behaviour of non-Newtonian thixotropic fluid [2, 7, 9, 10] (carbonatation mud is a thixotropic substance), a principle of calculating pressure drop for flow of such a fluid in a horizontal pipe [2,12] and a new method for transportation of undiluted carbonatation mud [6, 8].

Our present investigation deals with the problem of two-phase flow of gas and non-Newtonian thixotropic fluid. Such a transport enables power saving in comparison with single phase transport of carbonatation mud in a pipe.

The aim of this study was:

— to formulate a simple flow model of two-phase flow of non-Newtonian thixotropic fluid-gas mixture,

— to determine an optimum energy consumption in two-phase transport of undiluted carbonatation mud in a sugar factory.

A MODEL OF TWO-PHASE FLOW

The following assumptions in constructing a model of two-phase flow of gas and non-Newtonian thixotropic fluid in horizontal pipe were made (Fig. 1).

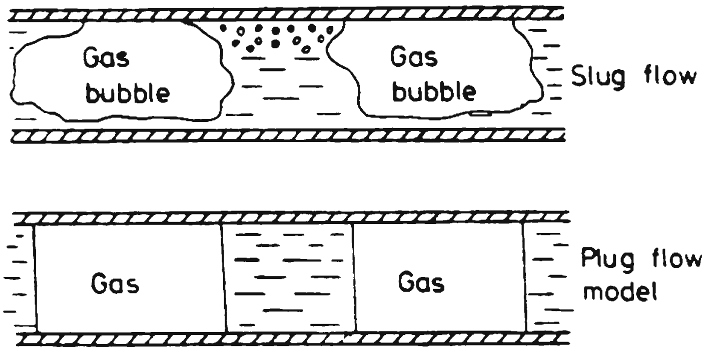

Fig. 1. The plug flow model

1. The gas and liquid are formed into discrete flat-ended plugs, each filling the whole cross-section of the pipe.
2. The pressure gradient along the gas plugs is negligible.
3. The pressure gradient along the liquid plug is the same as that for liquid flowing alone at the linear velocity of the liquid-gas mixture.
4. Rheological behaviour of fluid is described by the model proposed by Kemblowski and Petera [10,11].

Taking into account these assumptions the average two-phase pressure gradient may be defined by

$$\left(\frac{\Delta P}{L}\right)_{tp} = \lambda_{tp}\frac{V_{ns}^2 \varrho_L \xi_L}{2D} \tag{1}$$

where λ_{tp} is the two-phase friction factor, V_{ns} is the nonslip velocity, defined by eq. $V_{ns} = V_{SL} + V_{SG}$, ξ_L is the input volume fraction of liquid, $\xi_L = V_{SL}/(V_{SL} + V_{SG})$, V_{SL}, V_{SG} are superficial liquid and gas velocities, respectively, and D is the pipe diameter.

For the flow of liquid alone at the same superficial velocity V_{SL} the average pressure gradient $\left(\frac{\Delta P}{L}\right)_{SL}$ is defined by

$$\left(\frac{\Delta P}{L}\right)_{SL} = \lambda_{SL}\frac{V_{SL}^2 \varrho_L}{2D} \tag{2}$$

Combining eqs. (1) and (2) one can write an expression for the drag ratio Φ_L^2 in the form

$$\Phi_L^2 = \frac{\left(\frac{\Delta P}{L}\right)_{tp}}{\left(\frac{\Delta P}{L}\right)_{SL}} = \frac{1}{\xi_L}\frac{\lambda_{tp}}{\lambda_{SL}} \tag{3}$$

The mean values of the friction factor λ_{SL} during the flow of thixotropic fluid in a pipe was presented by Kemblowski and Petera [12] in the form

$$\lambda_{SL} = \frac{64}{Re'_{SL}}\left\{1-(1-Se_{SL})De_{SL}\left[1-\exp\left(-\frac{1}{De_{SL}}\right)\right]\right\} \tag{4}$$

where Re'_{SL} is the generalized Reynolds number of Metzner and Reed [14], De_{SL} is the Deborah number, and Se_{SL} is the structure number.

The friction faction for two-phase flow λ_{tp} was defined in the analogical form as for the case of a single phase flow

$$\lambda_{tp} = \frac{64}{Re'_{tp}}\left\{1-(1-Se_{tp})De_{tp}\left[1-\exp\left(-\frac{1}{De_{tp}}\right)\right]\right\} \tag{5}$$

Dimensionless numbers in eq. (5) may be expressed by the following equations

$$Re'_{tp} = \frac{1}{\xi_L^{2-n}}Re'_{SL} \tag{6}$$

$$Se_{tp} = \xi_L^{n-m}Se_{SL} \tag{7}$$

$$De_{tp} = \frac{1}{\xi_L}De_{SL} \tag{8}$$

where m,n are the rheological parameters of thixotropic fluid [10,11]

Introducing eqs. (4) and (5) to eq. (3) one obtains the final form of the equation for drag ratio Φ_L^2 in the two-phase flow of gas and thixotropic fluid in a horizontal pipe

$$\Phi_L^2 = \xi_L^{1-n}\frac{1-(1-\xi_L^{n-m}Se_{SL})\frac{De_{SL}}{\xi_L}\left(1-e^{-\frac{\xi_L}{De_{SL}}}\right)}{1-(1-Se_{SL})De_{SL}\left(1-e^{-\frac{1}{De_{SL}}}\right)} \tag{9}$$

According to the proposed model of flow the drag ratio is a function of three dimensionless numbers

$$Se_{SL} = \frac{\left(\frac{3\ m+1}{4\ m}\right)^{m} \varkappa_0}{\left(\frac{3\ n+1}{4\ n}\right)^{n} \left(\frac{8\ V_{SL}}{D}\right)^{n-m}} \tag{10}$$

$$De_{SL} = \frac{3\ m+1}{m+1} \frac{V_{SL}\Theta}{L} \tag{11}$$

where: $\varkappa_0$ — initial value of structural parameter of thixotropic fluid,
Θ — natural time of thixotropic fluid.

and

$$\xi_L = \frac{V_{SL}}{V_{SL}+V_{SG}} \tag{12}$$

Equation (9) is a generalization of the equation for the two-phase flow of non-Newtonian purely viscous liquid. In the case when $De \rightarrow O$, eq. (9) is simplified to the equation

$$\Phi_L^2 = \xi_L^{1-n} \tag{13}$$

proposed by Richardson [1,4,5] for non-Newtonian puerly viscous fluid.

In the case when natural time of thixotropic liquid is very long $\Theta \rightarrow \infty$, e.g. $De \rightarrow \infty$ eq. (9) is simplified to the form

$$\Phi_L^2 = \xi_L^{1-m} \tag{14}$$

A two-phase system of non-Newtonian thixotropic liquid-gas behaves as the two-phase system of non-Newtonian viscous liquid-gas with different rheological parameter m.

The solution of eq. (9) is presented in Fig. 2.

EXPERIMENTAL RESULTS

The presented model of flow was checked experimentally. As experimental media industrial carbonatation muds of different concentration were used. Typical results for two-phase flow of 55.5% carbonatation mud and gas mixture are shown in Fig. 3. From Fig. 3 and numerous data collected the following qualitative conclusions could be drawn.

1. For any sample of carbonatation mud drag reduction passes throught a maximum (Φ_L^2 a minimum) and at higher air rates the average pressure gradient will increase.
2. The minimum value of Φ_L^2 decreases as the liquid rate is reduced.

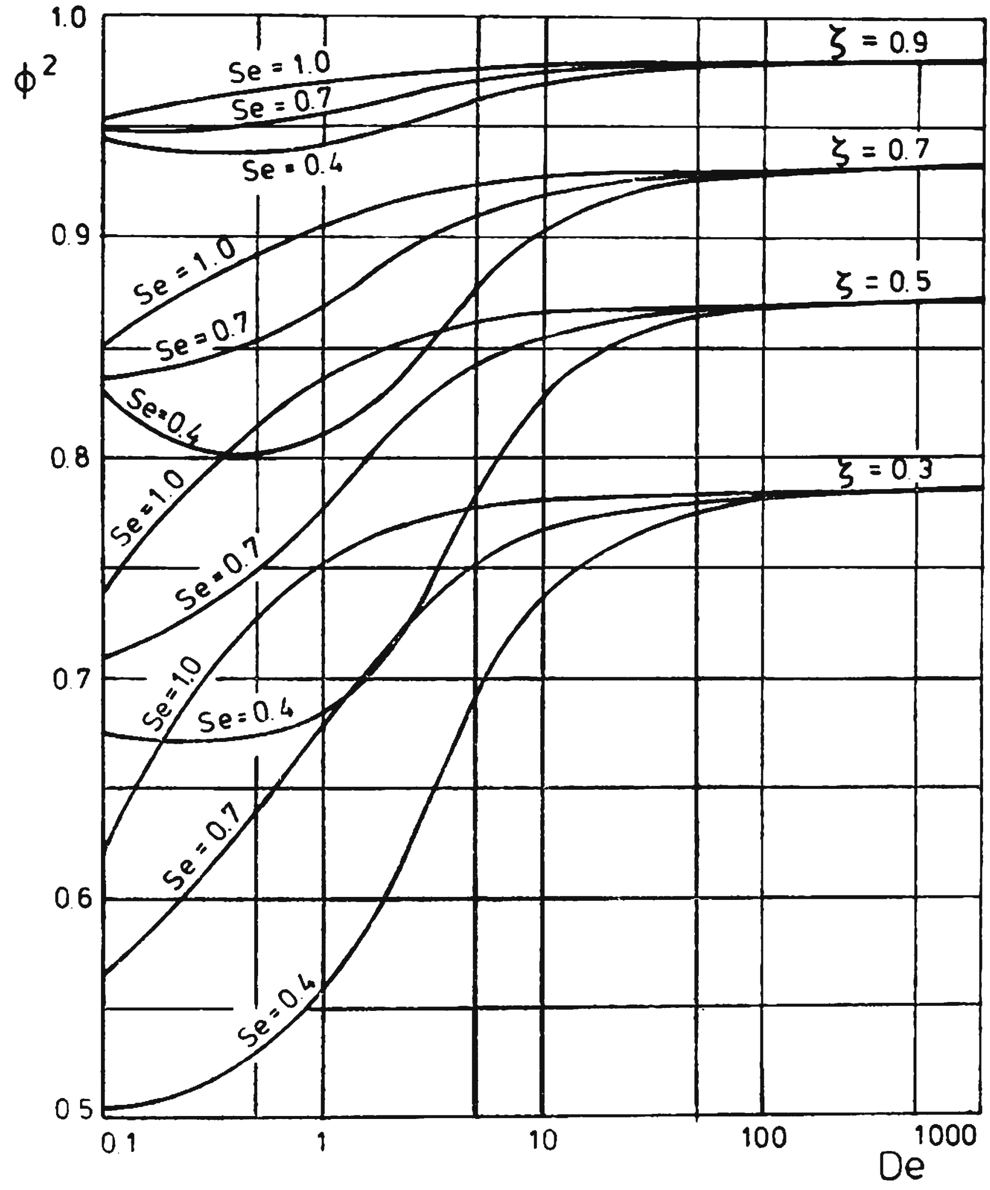

Fig. 2. Dependence of the drag ratio Φ_L^2 on the Deborah number for two-phase flow of thixotropic fluid; rheological parameters of fluid: m = 0.8, n = 0.5

Reduction in axial pressure gradient of up to 60% was obtained. In Fig. 4 the value of drag ratio predicted from the proposed model of flow $(\Phi_L^2)_{pred}$ — eg. (9), was compared with those obtained experimentally $(\Phi_L^2)_{exp}$. It can be seen that the preliminary experimental results confirmed the applicability of the proposed model of flow.

OPTIMUM ENERGY CONSUMPTION IN TWO-PHASE TRANSPORT

As has been described above, the injection of air into a horizontal pipe carrying a non-Newtonian thixotropic liquid may results in a significant reduction in the average pressure gradient. However, the air must first be compressed to a pressure exceeding that at the point of injection into the pipeline. Thus, the reduction in power required by the pump must be offset by the power required by the air compressor.

In order to take into account the difference between the total power required by the pump in two-phase and single-phase flow one may introduce a coefficient

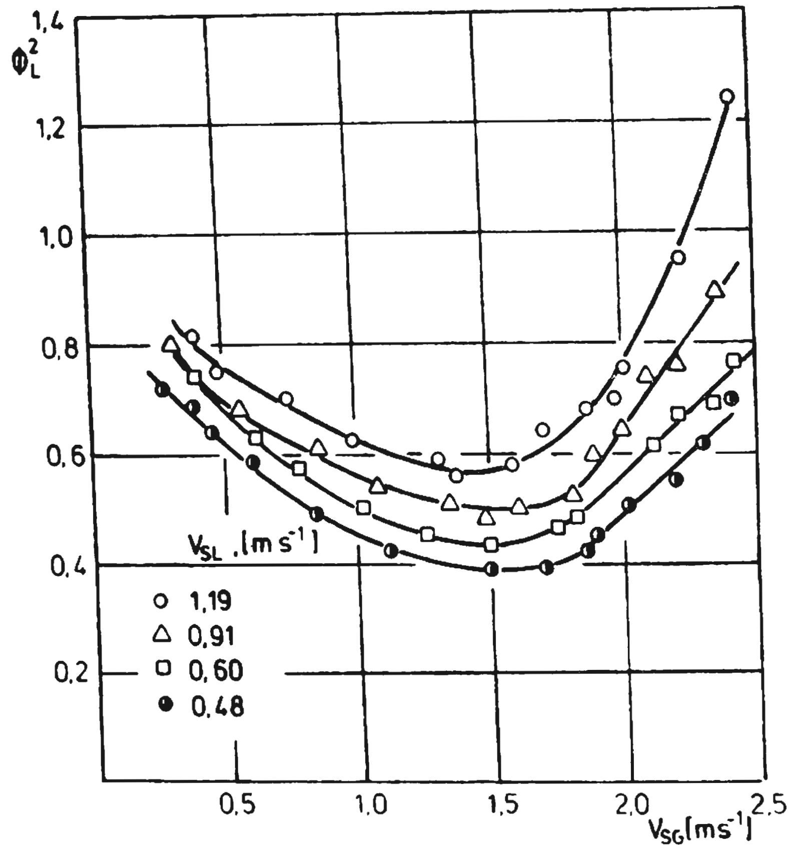

Fig. 3. Drag ratio for the cocurrent flow of air and 55.5% undiluted carbonatation mud in a 30 mm diameter horizontal pipe

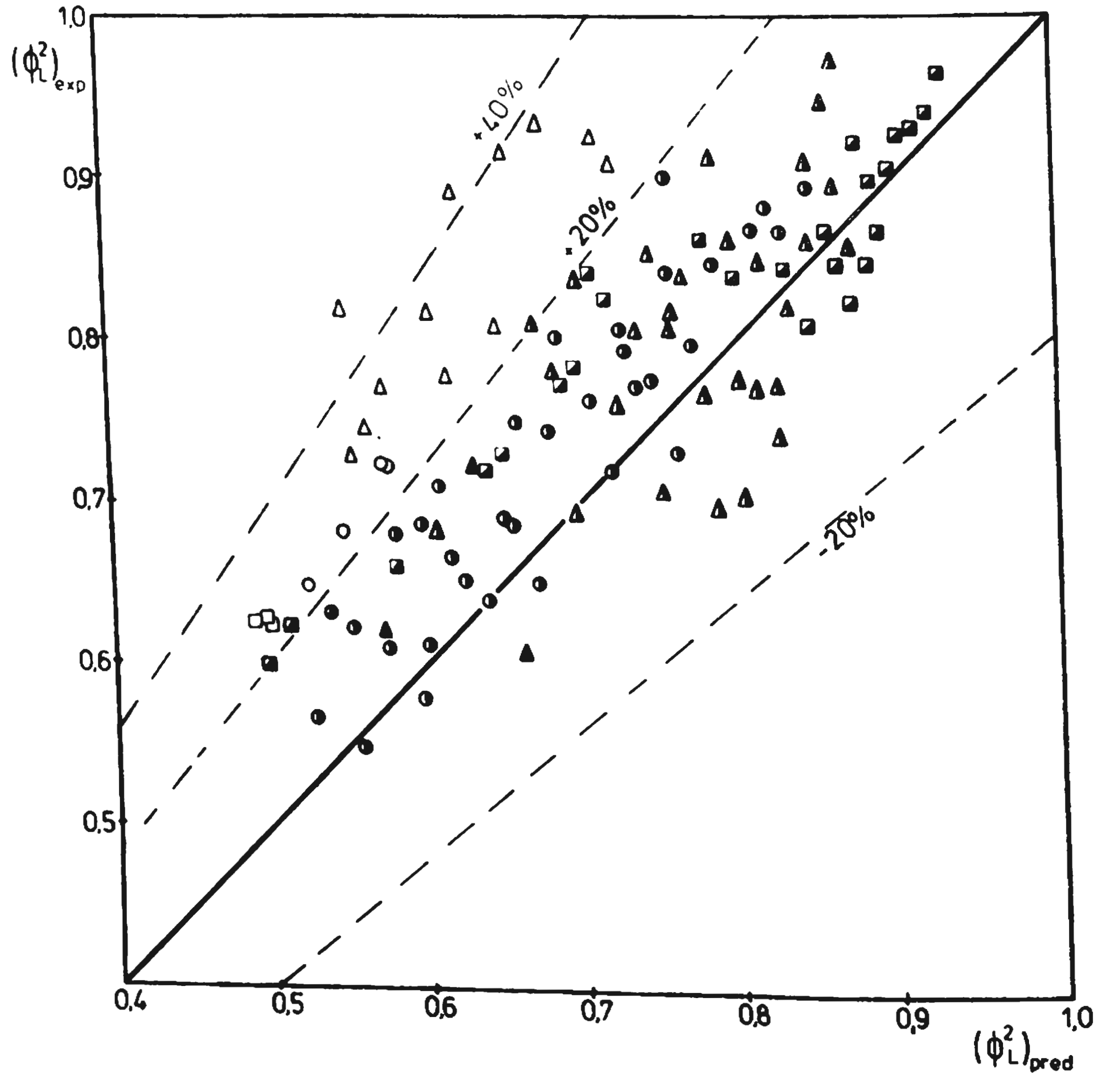

Fig. 4. Comparison of experimental and predicted from eq. 9 drag ratios for two-phase flow of undiluted carbonatation mud; mass concentration of mud: △ 47.9%, ○ 55.5%, □ 58%

of power saving Ψ defined as follows [1]

$$\Psi = \frac{\Delta N}{N_{SL}} = \frac{N_{SL} - N_{TP} - N_{SG}}{N_{SL}} \tag{15}$$

where ΔN is the overall power saving, N_{SL} is the power required by the pump for liquid flow alone, N_{TP} is the power required by the pump in the case of two-phase flow, N_{SG} is the power required by the air compressor.

Introducing in eq. (15) classical equations describing power required by the pump and air compressor and after a simple rearrangement one can obtain the final expressions for the coefficient of power saving in the form

$$\Psi = 1 - \Phi_L^2 - \frac{\eta_p}{\eta_c}\frac{v_{SG}}{v_{SL}}\left(\frac{P_{atm}}{\Delta P_{SL}} + \frac{\Phi_L^2}{2}\right)\ln\left(1 + \frac{\Delta P_{TP}}{P_{atm}}\right) \tag{16}$$

where: η_p, η_c are the efficiencies of a pump and compressor, respectively.

The investigations performed by ourselves [7,9] have shown that undiluted carbonatation mud is a thixotropic substance with a very long natural time $\Theta > 10^3$ s and rheological parameter $0.3 < m < 0.9$. For such a thixotropic fluid the drag ratio-from the proposed two-phase flow-model is described by eq. (14).

The maximum value of power saving coefficient Ψ_{max} as a function of the rheological parameter m with η_p/η_c as a parameter is presented in Fig. 5.

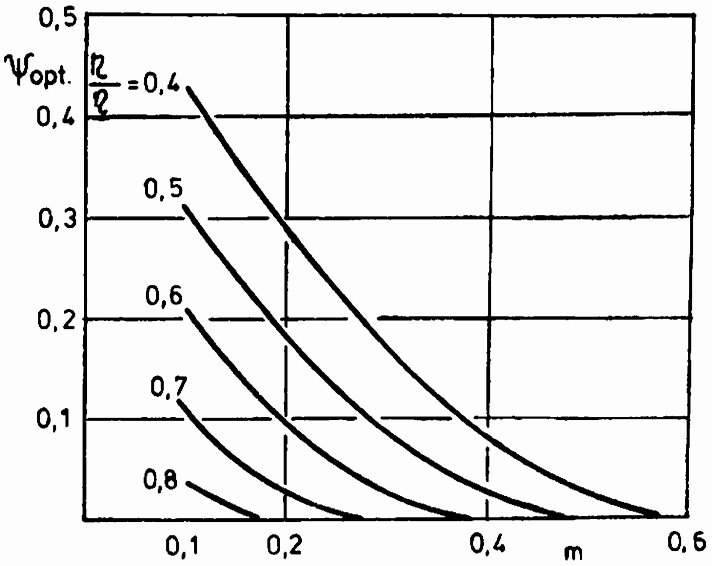

Fig. 5. The maximum value of power saving coefficient as function of the rheological parameter of thicotropic fluid m with η_p/η_c as a parameter

From Fig. 5 it follows that

a) the power saving becomes progressively greater as η_p/η_c decreases;

b) for most undiluted carbonatation mud in the two-phase flow a maximum value of the power saving coefficient is approximately 0.1-0.2 for typical values of pump and compressor efficiency.

There may be other advantages in injecting air. The undiluted carbonatation mud is very difficult to pump initially, but the presence of air will decrease the wetted surface area of the wall and reduce the inertia of the liquid to be accelerated on start-up. Consequently, at the commencement of pumping the liquid, both acceleration and friction losses along its length are lower than for mud flow alone and the pump is not required to develop such a large initial pressure.

This new method of transportation of undiluted carbonatation mud will be applied on a commercial scale in one of the Polish sugar factories.

CONCLUSIONS

1. A model of two-phase flow of gas and non-Newtonian timedependent fluid in a horizontal pipe is presented. The model was confirmed experimentally.
2. Using this model of flow a simple method for evaluating the optimum energy consumption in two-phase transport of undiluted carbonatation mud in a sugar factory is proposed.

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OPTIMUM ZUŻYCIA ENERGII PODCZAS TRANSPORTU DWUFAZOWEGO GAZ — NIEROZCIEŃCZONY OSAD SATURACYJNY

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Streszczenie

Opracowano nową metodę transportu nierozcieńczonego osadu saturacyjnego w cukrowniach. Jest ona oparta na przepływie dwufazowym w przewodzie układu płyn nienewtonowski-gaz. Umożliwia ona uniknięcia wszystkich niedogodności tradycyjnej metody transportu osadu saturacyjnego (duże ilości uciążliwych ścieków, znaczne zanieczyszczenie środowiska naturalnego) oraz uzyskanie znacznych oszczędności energetycznych.

Przedstawiono teoretyczny model przepływu dwufazowego w poziomej rurze układu reologicznie niestabilny płyn nienewtonowski-gaz (rys. 1). Zgodnie z zaproponowanym modelem parametr Lockharta-Martinellego Φ_L jest funkcją trzech liczb bezwymiarowych: liczby strukturalnej płynu Se, zmodyfikowanej liczby Debory De oraz wlotowego udziału płynu w mieszaninie dwufazowej ξ_L (rys. 2).

Model teoretyczny przepływu był testowany eksperymentalnie. Jako media doświadczalne stosowano przemysłowy osad saturacyjny o trzech różnych stężeniach. Doprowadzenie gazu do przewodu, w którym płynie osad saturacyjny powoduje znaczne obniżenie oporów przepływu w porównaniu z oporami przepływu tej samej ilości osadu w przepływie jednofazowym. Uzyskano maksymalne obniżenie oporów przepływu wynoszące ok. 60% (rys. 3). Wyniki eksperymentalne potwierdziły słuszność zaproponowanego modelu przepływu (rys. 4).

Stosując ten model przepływu opracowano prostą metodę określania minimum zużycia energii podczas transportu dwufazowego osadu saturacyjnego w cukrowniach (rys. 5).