INVESTIGATION OF THE EFFECTS OF ORGANIC ADDITIVES ON THE HYDRAULIC RESISTANCE AND HEAT TRANSFER IN A FLOW

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Results are given of a study of the effects of organic additives on the hydraulic resistance and heat transfer in turbulent flow.

The reduction of hydraulic resistance in pipe lines is of well known importance. Such reduction is found not only when solid particles (i.e. flowing suspensions) are added to a homogeneous phase but also with solution of organic additives.

The lack of semi-quantitative theory of the effects of such additives on frictional resistance and heat transfer has led to extensive experimental work to determine both the average and fluctuating parameters in turbulent flow conditions [1-10].

Experimental data from numerous sources allowed qualitative analysis of phenomena in turbulent flow with very low concentrations of organic additives. Using semi-empirical theories of homogeneous turbulence and assumptions from the experimental results, various authors have obtained equations for the averaged velocities and frictional resistances which agree well with the experimental data [8, 9, 11, 12].

Noting the great theoretical and practical value of the phenomenon being considered, and some discrepancies in the published data, the present authors have further studied hydrualic resistance and heat transfer with a selection of organic additives.

The additives tested were polyethylene oxide (PEO), polyacrylic amide (PAA), various alcohols (glycerine, propyland polyvinyl alcohol), polyisobutylene, poly-N-(N-phenyl)-vinyl naphthylamide (PPVNA with cyclic structures. The properties of additives are given in Table 1.

Tests of the effects of these additives were carried out systematically. A regular non-symmetrical 2×3 matrix was used. The two factors which were optimized were the additive concentration and the flow temperature. Adequate data for regression analysis by statistical methods were obtained. Hence for PAA with molecular weight of $12.9 \cdot 10^6$

$$\hat{y} = 24.85 + 2.725x_1 - 2.159\,x_2 - 9.67x_1^2 ,$$

$$\hat{y}' = 42.67 + 3.1x_1 - 3.35x_2 - 14.36x_1^2 ,$$

where x_1 is the additive concentration; x_2 is the flow temperature. These equations show that for all the additives, the variations in hydraulic resistance and heat transfer with additive concentration are quadratic and with temperature they are linear.

Laboratory experiments were made using a cylindrical heat exchanger with electrical heating. The test section consisted of copper pipe $\varnothing 18 \times 2$ mm with an upstream stabilization length of 60 diameters. The static pressure loss was measured with a two-fluid U-tube manometer. The flow rate was determined by measuring the volume for a given time. The temperatures of the pipe wall and the flow were measured with differential chromel—alumel thermocouples and an M 95 millivolt meter. The Reynolds numbers were in the range $8 \cdot 10^3$ to $6 \cdot 10^4$. The test section formed part of a closed loop apparatus in which the inlet temperature was maintained constant. A centrifugal pump was used for circulating.

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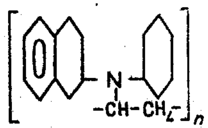
TABLE 1. Characteristics of Organic Additives

Additive	Structural formula	Molecular weight	Additive concentration, weight %	Solvents	Inlet flow temperature	Remarks
PEO	$[CH_2-O-CH_2]_n$	$9 \cdot 10^6$	$10^{-6}-10^{-2}$	water glycerine	20—80	pH=3–13
PAA	$[CH_2-CH(C{=}O\,NH_2)-]_n$	$4{,}68 \cdot 10^6$ $6{,}03 \cdot 10^6$ $9{,}79 \cdot 10^6$ $12 \cdot 10^6$	$10^{-5}-10^{-2}$	water kerosene TS-5 glycerine	20—80 20 50—60	pH=3–13
Poly-N-(phenyl)-vinyl naphthylamide		2000	$2 \cdot 10^{-2}-2 \cdot 10^{-1}$	water	30	distilled water
Polyisobutylene	$[-CH_2-CH(CH_3)-CH_2-]_n$	250000	$10^{-3}-10^{-1}$	transformer oil	80	pH=7
a) propyl alcohol	$CH_3-CH_2-CH_2-OH$	60	0,1—2	water	20—40	distilled water
b) glycerin	$CH_2OHCHOHCH_2-OH$	92	0,05—0,1	water	20—40	the same
c) polyvinyl alcohol	$[-CH_2-CH(OH)-]_n$	2000	0,05—1	water	20—40	" "

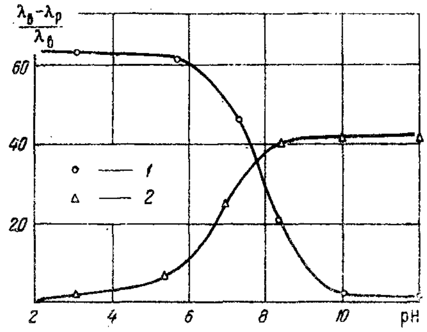


Fig. 1. Efficiency of additive action on pH of the medium: λ_B, hydraulic resistance coefficient for pure solvent; λ_p, hydraulic resistance coefficient for polymer additive solutions: 1) polyethylene oxide; 2) polyacrylamide.

Proving tests were made with distilled water without additive. The results agreed well with established data for friction coefficient and heat transfer.

The variables in the test program were the flow rate, the type and concentration of additive organic (pH 3 → 13) and inlet temperature.

The optimum concentrations were determined in each case. The greatest reduction in hydraulic resistance and improvement in heat transfer were obtained for PEO (for Re = 20000 = constant, c_{opt} = 0.006 weight %, the resistance was reduced by 39% and the heat transfer reduced by 65%). Other authors observed greater reduction up to 80% [13]. The lesser reductions reported here can be explained by a greater rate of breakdown of the PEO molecules in the pump.

The tests made with PAA of molecular weight $12.9 \cdot 10^6$ and less confirmed that it too reduced the hydraulic resistance and the heat transfer.

These tests showed that effects were dependent on molecular weight of the PAA and that, when this weight was increased with the concentration kept constant, the reductions in both heat transfer and hydraulic resistance were further increased. These results are in agreement with others [12, 13] showing that for a given additive the improvements are proportional to the product of the concentration and the molecular weight rather than to the concentration alone. (With Re = 20000 for molecular weight $12.9 \cdot 10^6$, $c_{opt} = 9 \cdot 10^{-3}$ weight %, the hydraulic resistance was reduced by 27% and the heat transfer by 46% and for molecular weight $4.7 \cdot 10^6$, copt = $4.7 \cdot 10^{-3}$ weight % the hydraulic resistance was reduced by 21% and the heat transfer by 39%.)

In tests of PEO and PAA in acids and alkalis, it was shown that when pH value increases from 7 to 10 the effects of the PEO decreased sharply and when the pH value was 12 the effects have fallen almost to zero. These effects were greatest in acid conditions. Figure 1 shows the contrasting behavior of PAA.

Tests were also made to determine the influence of temperature on the PEO and PAA additives. It was found that the reduction in hydraulic resistance by PEO fell with increasing temperature to almost zero at as low a temperature as 60°C; PAA is however less influenced by temperature and the maximum temperatures at which its effects are still appreciable are dependent on its molecular weight.

Tests with poly-N-(N-phenyl)-vinyl naphthylamine (molecular weight = 2000) show that this too reduced the hydraulic resistance and heat transfer (Re = 20000, c_{opt} = 0.16 weight % the reduction in hydraulic resistance was 27% and the reduction in heat transfer was 38%). These reductions critically depended on the concentrations.

It was therefore decided to check if any of the additive was being adsorbed on the pipe walls by analyzing the solution before and after tests. Specially prepared sample plates of the same material as the pipes were also placed in the flow. After the test, any additive adsorbed on these plates was desorbed. The changes in concentration in the solution were determined spectrophotometrically using a "Spectromom 203" instrument.

Other tests were made of the effects of PAA, PEO and polyisobutylene in organics (kerosene TS-5, transformer oil and glycerine) which all showed reduced hydraulic resistances. In glycerine (PAA of molecular weight $4.7 \cdot 10^6$, with Re = 12000, $c_{opt} = 5 \cdot 10^{-3}$ weight %) the reduction in hydraulic resistance was 23%, in kerosene (PAA of molecular weight $4.7 \cdot 10^6$ with Re = 38000 $c_{opt} = 3 \cdot 10^{-3}$ weight %) the reduction in hydraulic resistance was 15%.

For large Reynolds numbers (above 40000) with PAA solutions an increase in hydraulic resistance was found compared with the resistance of pure solvent. This corresponds with the beginning of normal resistance to flow as confirmed [12] but is not in good agreement with experimental data [13]. (Polyisobutylene in transformer oil at Re = 12000, $c_{opt} = 2 \cdot 10^{-3}$% reduced the hydraulic resistance by 18%, heat exchange by 25%.)

From tests with alcohol additives, it was established that as the number of carbon atoms in the chain increases (from 3 to 1000) the hydraulic resistance decreases. PVA (with Re = 20000, c_{opt} = 0.1 weight % reduces the resistance by 23% propyl alcohol (Re = 20000, copt = 1 weight %) increases hydraulic resistance by 10%. In tests of the influence of hydroxyl groups in the alcohol molecule it was shown that change in the number of such groups from one in propylene to three in glycerine results in increasing the hydraulic resistance and heat transfer, propylene (c_{opt} = 1 weight %) increases the hydraulic resistance by 10% and glycerine (c_{opt} = 1.1 weight %) increases it by 30%.

These effects of spirit additives, in particular of glycerine can be explained by the structure of the water. Additives in the flow produce increased "strucuting" of the water, i.e. thickening and increased viscosity, the latter resulting in increased hydraulic resistance [14].

Some of the additives tested are now being further investigated for industrial use.

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