AN EXPERIMENTAL STUDY OF HYDRAULIC RESISTANCE TO THE ASCENDING FLOW IN FILM-TYPE DISTILLERS

V. N. Slesarenko and G. A. Gudakov

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The hydraulic drag coefficient in an ascending thin air–water film was studied as a function of the wetting rate and of the air velocity. Formulas have been derived for calculating this coefficient.

When the thermophysical characteristics of thermal distillation of seawater are studied, for the purpose of improving the working processes in existing installations and for the purpose of developing new types of such installations, it is a problem to design means by which the rate of heat and mass transfer can be improved modally.

A significant modal improvement of the heat transfer is achieved in thin-film apparatus with ascending and descending flow.

Data on the hydraulic drag in ascending thin gas– or vapor–liquid films are rather scarce [1-4] and often contradictory.

The authors have tried to verify and refine existing data, to obtain new data on the hydraulic drag in an ascending air–water film, to derive mathematical relations for the hydraulic drag coefficient, and also to visually track the stability of various flow modes.

The active segment of the test apparatus consisted of a Pyrex glass tube, 1300 mm long and with an inside diameter equal to 26 mm, around which a Nichrome heater wire 2 mm in diameter had been wound with Nuvel and asbestos rope as thermal insulation.

The end segments of the tube were inserted through packing seals into special chambers, the lower one provided with a stack assembly to facilitate a stable ascending film flow. The initial film thickness was regulated by interchangeable stacks.

The air flow was stabilized within an inlet segment 150 mm long into the lower chamber.

In the upper chamber we had installed a centrifugal separator for separating the gas from the liquid. The incoming air and water were heated with electric heaters installed between the flow meters and the lower chamber: the power of the water heater was 7 kW, that of the air heater was 2.5 kW, and that of the active test segment was 6.5 kW. The air heater and the water heater were energized from the ac network, while the heater for the active test segment was energized from a dc generator whose power output could be regulated smoothly from 0.5 to 6.5 kW.

The temperatures of the water heater and the air heater were controlled by readings of contact thermometers and held stable within ±1°K. The temperature of water and air in the lower chamber was checked with mercury thermometers on a scale with 0.5°K divisions. The air flow rate was measured with a standard diaphragm $D_y = 50$ mm and $m_d = 0.16$; the water flow rate was measured with diaphragms 2 mm and 4 mm in diameter which had been mounted on the 10 mm (diameter) tube and had been calibrated by the volumetric–gravimetric method. All operating modes could be duplicated.

The hydraulic drag was studied at an air velocity W_A ranging from 7 to 35 m/sec, referred to the total inside cross section of the tube, at a surface wetting rate Γ_V ranging from $5.5 \cdot 10^{-5}$ to $55.2 \cdot 10^{-5}$ m²/sec. The initial film thickness δ_0 lay in the range 0.5 to 2.5 mm. In order to explore the effects of water and air viscosity on the hydraulic drag, we varied the temperature of water

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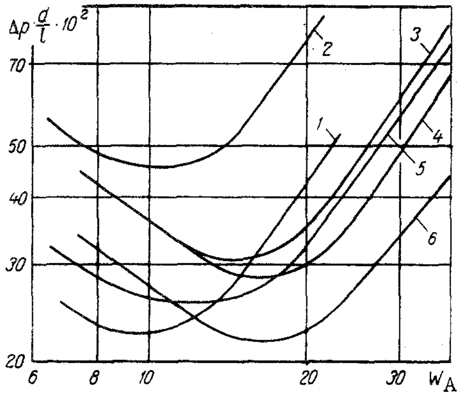

Fig. 1. Comparison between our results and the data in [1-4]: 1) data in [1]; 2) [2]; 3, 4) our data; 5) [3]; 6) [4]; air velocity W_A (m/sec), referred pressure drop $\Delta p(d/l) \cdot 10^2$ (N/m^2).

and air from 285 to 368°K. The flow modes during boiling of the liquid were also analyzed. The tests were performed under nearly atmospheric pressure.

The values of air velocity and wetting rate were stipulated on the basis of a model performance under nearly real conditions with an ascending film flow. The lower limit of the velocity, moreover, was determined by stalling.

Visual inspection as well as measurements of the said parameters have established a satisfactory degree of stability in the ascending film, over the entire range of air velocities and wetting rates.

At wetting rates below (14-16) $\cdot 10^{-5}$ m^2/sec and air velocities up to 13-16 m/sec the ascending film flow was laminar – undular. At velocities of 22-26 m/sec there appeared periodically annular segments 1-3 cm wide which then ascended at a velocity of 2-3 m/sec without affecting the undular flow of the rest of the film. A further increase of the air velocity caused turbulization and the film because opaque. At wetting rates above (14-16) $\cdot 10^{-5}$ m^2/sec, with the air velocity W_A increasing, the transition from laminar – undular to turbulent flow occurred at air velocities of 18-20 m/sec.

The described pattern of an ascending film flow agreed entirely with the data in [5].

The amount of liquid lost behind the separator was negligible in all tests. At $\Gamma_V > (25\text{-}30) \cdot 10^{-5}$ m^2/sec and $W_A > 30$ m/sec large droplets were splashed away, which we explained by a flow constriction behind the separator. After a cone had been formed behind the separator 400 mm in height, no droplets were seen splashing beyond it even at the highest wetting rates and air velocities.

In order to compare these data with others, we evaluated then in terms of the relation

$$\frac{\Delta p d}{l} = f(W_A). \tag{1}$$

An analysis of the results has shown (Fig. 1) a close qualitative agreement with the data in [1-4] and also a quantitative agreement with [4]. As the dimensionless characteristic of hydraulic drag we have used the coefficient ξ in the Darcy equation

$$\Delta p = \xi \frac{l}{d} \frac{\rho W_A^2}{2}. \tag{2}$$

Dimensional analysis applied here will yield the hydraulic drag coefficient

$$\xi = A \, \mathrm{Re}_f^m \, \mathrm{Re}_A^k. \tag{3}$$

If one consider the effects of water and air viscosity on the hydrodynamics of film flow, by introducing a simplex group which includes the kinematic viscosity of water ν_f and of air ν_A, then Eq. (3) reduces to

$$\xi = A \left(\frac{\nu_f}{\nu_A}\right)^n \mathrm{Re}_f^m \, \mathrm{Re}_A^k. \tag{4}$$

An evaluation of the test results by the method of least squares on a model Minsk-22 computer has confirmed the validity of expressing the coefficient ξ according to relation (4) and then in a final form suitable for numerical evaluation.

For an air velocity W_A from 8 to 20 m/sec, Eq. (4) can be generalized without regard to the initial film thickness.

Thus, for the stipulated values of referred air velocity and with the thickness of the ascending film varied from 0.5 mm to 2.5 mm, the hydraulic drag coefficient can be expressed by the equation

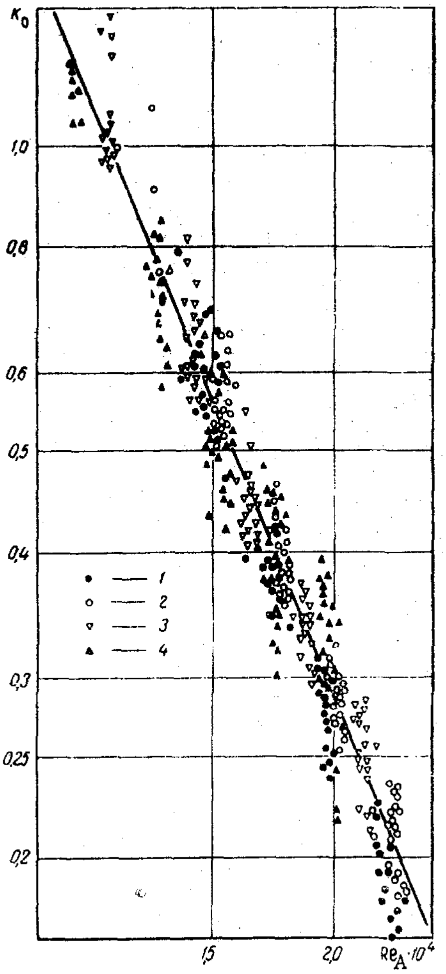

Fig. 2. Evaluation of test data in $\xi(\nu_f/\nu_A)^{-0.7}\,Re_f \sim Re_A$ coordinates: 1) 285; 2) 303; 3) 333; 4) 368°K.

TABLE 1. Coefficient A in Eq. (6) and Values of Δ for Various Film Thicknesses

δ_0, mm	A	Δ, %
0,5	251,5	7,1
1,0	240,1	6,0
1,5	196,4	7,4
2,0	200,0	7,6
2,5	213,8	7,2

$$\xi = 4.87 \cdot 10^9 \left(\frac{\nu_f}{\nu_A}\right)^{0.7} Re_f^{1/3} Re_A^{-2.38}. \qquad (5)$$

The standard deviation of test data from the theoretical values does not exceed 11%.

The test data in K_0, Re_A coordinates ($K_0 = \xi(\nu_f/\nu_A)^{-0.7}\,Re_f^{-1/3} \sim Re_A$) have been plotted in Fig. 2 against the theoretical relation (5).

It is quite evident that our test data agree closely with the derived relation.

For referred air velocities above the indicated critical level, the initial film thickness has an appreciable effect on the magnitude of coefficient ξ, namely:

$$\xi = A \left(\frac{\nu_f}{\nu_A}\right)^{0.56} Re_f^{0.55} Re_A^{-0.92}. \qquad (6)$$

The value of coefficient A and the standard deviation of test results Δ is shown in Table 1 for various values of the initial film thickness.

An analysis of relations (5) and (6) indicates that, during turbulent flow, the coefficient ξ is much less affected by the viscosity of water and slightly less by the viscosity of air.

Evidently, in this case the effect of water viscosity on the hydraulic drag coefficient is attenuated by the appearance of dispersive-annular streamers of the two-phase medium and by the occurrence of mass transfer via droplets moving between the film and the vaporous mainstream.

A comparison between the test data and Eq. (6), evaluated in K_0', Re_A coordinates $K_0' = \xi(\nu_f/\nu_A)^{-0.56}\,Re_f^{-0.55} \sim Re_A$, is shown in Fig. 3.

The segregation of test points in Fig. 3 according to different film thicknesses can be explained by the different amounts of energy required for the acceleration of a liquid film, inasmuch as the mean film thickness is governed by such groups as the Reynolds numbers Re_f and Re_A while the mass of liquid at the entrance is a function of δ_0.

We have also evaluated the data in K_0'', Re_A coordinates ($K_0'' = \xi Re_f^{-1/3} \sim Re_A$), as shown in Fig. 4 for the entire range of air velocity and matching the results in [2-4].

The agreement between all test results is satisfactory, according to the graphs, but the geometry of the active test segment seems to have an appreciable effect on the ascending flow of thin films, although the trend of the $K_0'' = \xi Re^{-1/3} = f(Re_A)$ relation is retained. Conditions under which water enters the active test segment have also an effect on the hydraulic drag coefficient, as has been already mentioned earlier.

Since the effect of tube diameter and tube length on the hydraulic drag coefficient have not been analyzed here, hence formulas (5) and (6) may be recommended for use only under conditions such as stipulated here.

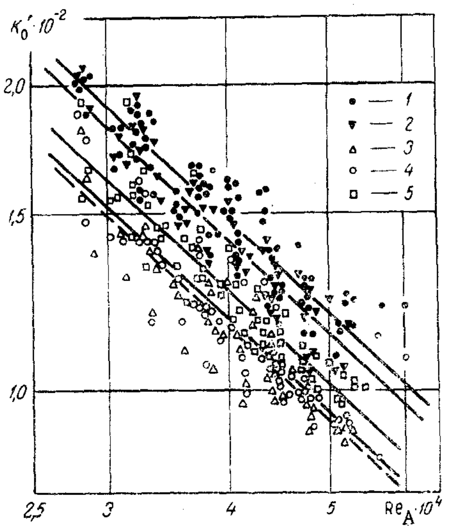

Fig. 3

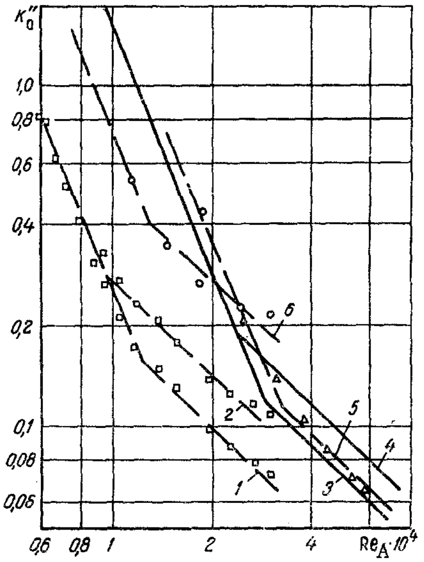

Fig. 4

Fig. 3. Comparison between test data and the theoretical relation (6): 1) δ_0 = 0.5 mm; 2) 1.0; 3) 1.5; 4) 2.0; 5) 2.5.

Fig. 4. Comparison between data by various authors according to relations (5) and (6): 1) $\Gamma_V = 17.5 \cdot 10^{-5}$ m²/sec; 2) $\Gamma_V = 45 \cdot 10^{-5}$ m²/sec (tube diameter 13 mm for 1) and 2) [3]); 3) $\delta_0 = 2.0$ mm; 4) $\delta_0 = 0.5$ mm ($\Gamma_V = 52 \cdot 10^{-5}$ m²/sec for 3) and 4), our data); 5) $\Gamma_V = 50.3 \cdot 10^{-5}$ m²/sec with tube diameter 28 mm [4]; 6) $\Gamma_V = 18.7 \cdot 10^{-5}$ m²/sec with tube diameter 17 mm [2].

NOTATION

Δp	is the hydraulic resistance in the active segment with a guide stack, N/m^2;
l, d	are the geometrical dimensions of the active segment, m;
ρ	is the density of the air stream, kg/m^3;
W_A	is the air velocity referred to the total tube cross section, m/sec;
$Re_f = 4\Gamma_V/\nu_f$	is the Reynolds number for the film;
$Re_A = W_A d_{out}/\nu_A$	is the Reynolds number for the air stream.

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