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ENTRAINMENT IN CONDENSING ANNULAR FLOW

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Abstract—Experiments were carried out on low pressure, steam–water, condensing annular flow in a 38.1 mm i.d. horizontal tube. The velocity of the steam at inlet was in the range 97–186 m/s.

Measurements of the liquid film flow rate at the end of the test section, which arose as a result of condensation, entrainment, and deposition, were made by extracting the film through a porous sinter bush. The liquid flow rate in the vapour core at exit was deduced from these measurements together with a heat balance on the condenser section.

These results were compared with three correlations for entrainment developed from air–water studies. On the basis of the experimental data available, there was sufficient agreement in one case to warrant further investigation.

1. INTRODUCTION

Annular flow is one of the most common two-phase gas–liquid flow regimes encountered in industrial equipment. In certain cases, the separated flow model, in which the liquid flows as a thin symmetrical film along the tube wall with the gas or vapour occupying the central core, may be sufficient for design purposes. However, the interaction between the two phases, whereby liquid droplets are entrained into the gas stream from the tips of waves travelling along the gas/liquid interface and rejoin it by deposition, is responsible for some of the important associated phenomena, such as the wall dry-out condition.

In the case of horizontal flow, gravity plays an important role in distorting the shape of the liquid film and the mechanism by which the presence of a liquid film is maintained at the upper surface of the tube is not yet clearly understood.

Air–water studies have made an important contribution to the knowledge of the parameters which govern the rates of entrainment and deposition but it is necessary to establish whether or not these relationships can still be used for the design of a system in which heat and mass transfer are occurring.

2. ENTRAINMENT CORRELATIONS

It is of interest to consider some of the methods that are currently available, and are at present being developed for the calculation of the entrained fraction. Hughmark (1973) supposed that entrainment was a function of film thickness. Data from Collier *et al.* (1961), Alia *et al.* (1965) and Cousins *et al.* (1965) were used to obtain a correlation between the volumetric flow ratio $W_E\rho_G/W_G\rho_L$ and $y_G{}^+$, the dimensionless film thickness based on the gas properties. Here W_G is the mass flow rate of vapour, W_E the mass flow rate of entrained liquid and $y_G{}^+$ is given by $[(mV_G)/v_G]$ where m is the film thickness and V_G the vapour core velocity. Entrainment appeared to begin at a minimum $y_G{}^+$ of about 35, which is the transition between partially turbulent and fully turbulent conditions in single-phase turbulent flow.

Paleev & Filippovich (1966) plotted experimental results for air–water mixtures from different sources to obtain a correlation between W_L/W_T and $(\bar{\rho}/\rho_L)\{[(\mu_L V_G)^2]/\sigma\}$ where

W_L is the mass flow rate of liquid in the film, W_T is the total mass flow rate of liquid and $\bar{\rho}$ is given by

$$\rho_G\left[1+\frac{W_T(1-W_L/W_T)}{A\rho_G V_G}\right]$$

where A is the channel cross-sectional area.

Hutchinson & Whalley (1972) argued that the dominant effect relevant to entrainment was the existence of sufficient local shear stress at the interface to overcome the containment effect of surface tension. They proposed that the rate of entrainment should be characterised by a dimensionless group $[(\tau_i m)/\sigma]$, where τ_i is the interfacial shear stress. Although no direct measurements of entrainment rate were available, they tested this hypothesis by plotting $[(\tau_i m)/\sigma]$ against the concentration of liquid droplets in the gas core. Experimental results, taken from air–water and air–alcohol systems in tubes of varying diameter, were selected for those cases which satisfied approximately the condition of hydrodynamic equilibrium. In this situation the rate of entrainment of droplets from the liquid film was equal to the rate of deposition of droplets back into the film. Since the rate of deposition was given by $K_D C_E$, the entrainment rate must be directly proportional to the concentration of liquid droplets in the core, C_E. Here K_D is the mass transfer coefficient.

The work reported here forms part of a larger investigation (Guevara 1981) of the characteristics of condensing annular flow with a high vapour core velocity in a horizontal tube.

3. EXPERIMENTAL DETAILS

The experimental apparatus consisted of three major sections (figure 1): section A, a precondenser, where the quality at inlet to the test section was controlled by partial condensation, section B, where the condensing experiments were carried out, and the third one, C, where it was intended to study the deposition of liquid droplets.

The steam used for the experimental work was supplied by a boiler at 13.8 bar and

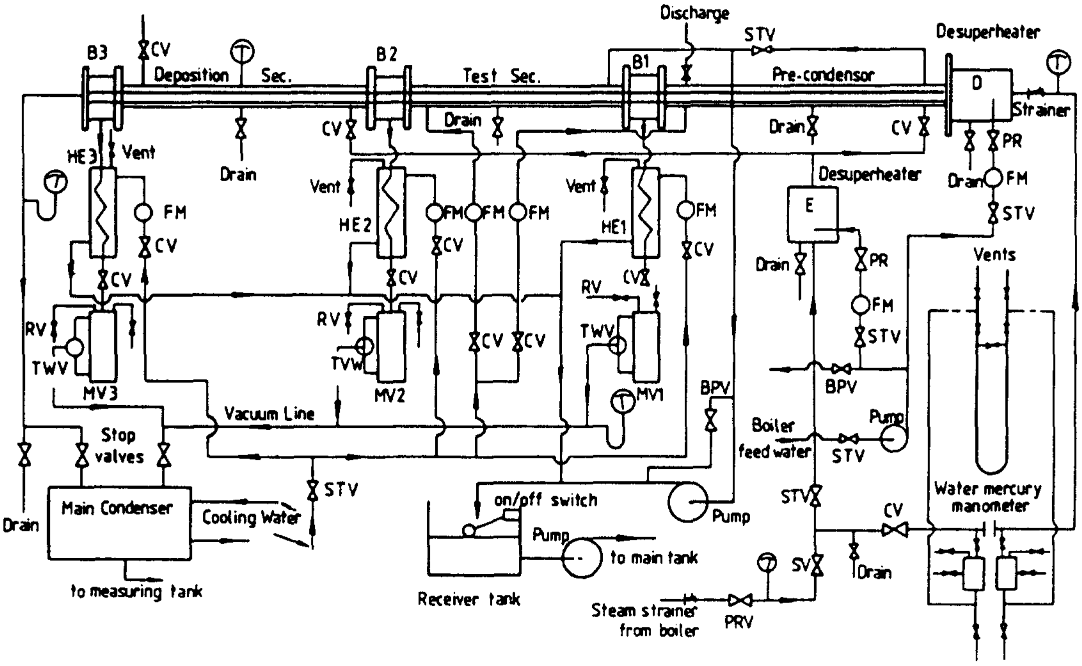

Figure 1. Flow diagram of experimental rig.

reduced to rig pressure before passing through a calibrated orifice plate and entering the desuperheater. The desuperheater was not used during these tests. The remaining uncondensed steam leaving the rig was passed through the main condenser and then to a measuring tank.

The precondenser was used to provide established conditions at entry to the test section. It consisted of a 5.0 m long horizontal stainless steel tube, 38.1 mm i.d., surrounded by a 66 mm i.d. steel tube, with cooling water passing counter currently through the annular space. This was followed by a liquid film removal unit (porous sinter bush B.1) which could be used to remove the liquid film at the end of the precondenser section if required.

The test condenser consisted of the thick-walled stainless steel tube 38.1 mm i.d., 5.08 mm wall thickness and 3.0 m long. The cooling jacket, in which the water flowed counter-currently, consisted of a stainless steel tube, 63 mm i.d.

The test condenser was provided with instrumentation to measure the tube wall temperature at a number of stations in the axial and circumferential direction, and the axial static pressure distribution. The cooling water temperature was also measured at a number of axial positions along the annulus.

The liquid film flow rate at the end of the test section was measured by extracting it through a porous sinter bush, B2. Care was taken to ensure that the bore was concentric and that there were no ridges at the various joints. Suction was applied to the outside of the sintered bush by connecting the annular space around it to a vacuum line leading to the main condenser. The extracted liquid, together with a small amount of steam withdrawn at the same time, was passed through a heat exchanger, HE2, and the resulting condensate was passed to a measuring vessel, MV2, before being returned to the main condenser.

Tests were carried out in which the condensing pressure was varied between 0.4–1.6 bar, the inlet quality between 0.55–1.0, and the inlet velocity between 97–186 m/s. Steady state conditions could be reached in any run within two hours, however, the system was run for a period of $2\frac{1}{2}$ hr before any measurements were recorded.

4. LIQUID FILM FLOW MEASUREMENTS

The processes of condensation, entrainment and deposition were responsible for the formation of the liquid film on the tube wall. At the end of the test section, the liquid film, together with some vapour, was withdrawn through a porous sinter device and passed through a heat exchanger where the vapour component was condensed. The liquid film flow rate was calculated from a heat balance on the heat exchanger.

In principle the method consisted of removing the liquid film along with varying amounts of vapour by altering the pressure differential across the sinter. The take-off characteristic of the sinter was drawn by plotting the total liquid condensate flow rate against the vapour flow rate. The undisturbed liquid film flow rate was found by extrapolating the straight line portion of the characteristic back to zero vapour take off.

During preliminary tests using this method, it was found that altering the amount of suction applied to the sinter changed the conditions at entry to the test section slightly. The pressure drop between the boiler reducing valve in the line from the boiler and the main steam condenser was constant. However, the resistance of the system changed when the setting on the extraction line from the sinter was altered since it was also connected to the main steam condenser. This resulted in slight change in the steam pressure at entry to the test section of between 0.15 to 0.25 bar. Therefore not all the points on the take-off characteristic corresponded to the same test section entry condition. In view of this it was decided to carry out the tests with the control valve regulating the rate of extraction fully open thereby applying the maximum available pressure differential across the sinter. The liquid film flow rate was calculated from a heat balance on the heat exchanger for this condition.

5. DATA REDUCTION

The interfacial shear stress was calculated from the momentum equation by subtracting the acceleration component from the local total pressure gradient, which was obtained from the measured pressure distribution along the tube. The local quality at any section was determined from a heat balance along the condensing section. An empirical correlation (Smith 1969) was used to calculate the void fraction, which was then used to compute the average velocity of each phase and the liquid film thickness. A correlation of the frictional pressure drop results in terms of the modified Lockhart–Martinelli parameters (to be published) has been achieved using this information which supports the validity of the procedure.

6. DISCUSSION OF RESULTS

The total amount of liquid present in the flow at the end of the test section was found by carrying out a step-wise heat balance along the test condenser. This was plotted against the experimentally measured liquid film flow rate (figure 2). In this graph points on the continuous line represent a condition in which all the liquid present in the tube at the end of the test section flowed in the form of a film along the tube wall and was extracted. The vertical distance between a test point and this line represents the quantity of liquid flowing in the vapour core which has arisen from the combined effects of entrainment and deposition along the tube.

It can be seen that most of the data points are positioned close to a smooth curve drawn through them although the scatter is occasionally rather large. This may have arisen as a result of the complexity of the experiments, which produced different conditions at the end of the test section, as well as some aspects of the performance of the porous sinter. The data is consistent in that tests with higher rates of condensation had a larger

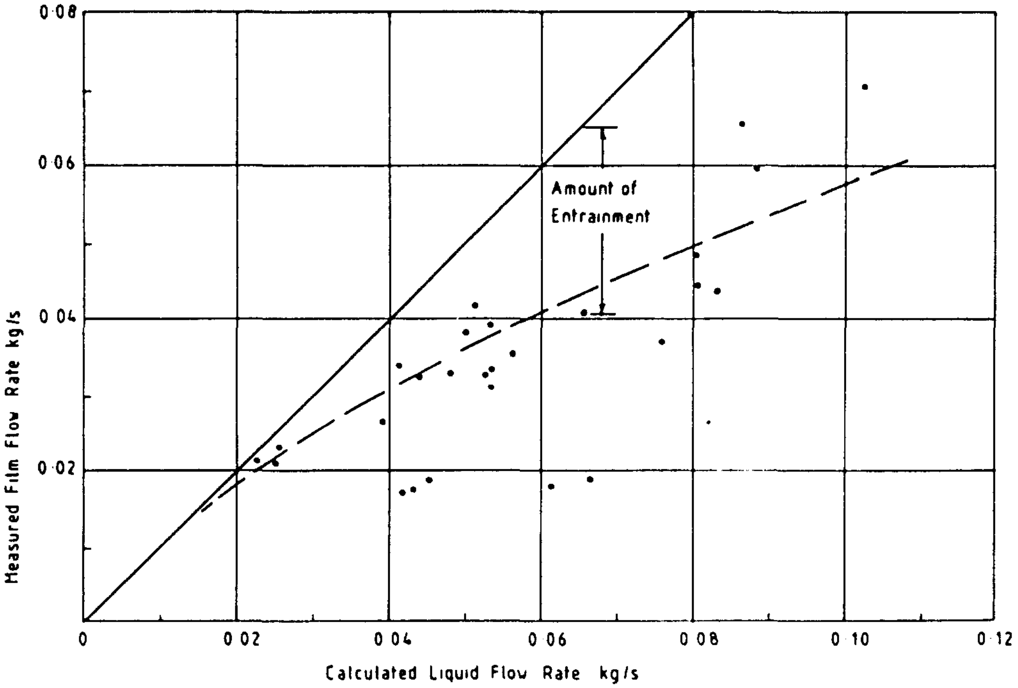

Figure 2. Comparison of measured and calculated liquid flow rates.

Table 1. Experimental results at the end of the test section

TEST NO.	P	W	x	W_L	W_e	τ_i	m	C_e	$\frac{\tau_i m}{\sigma}$
1	1.3212	0.1353	0.675	0.0324	0.0115	20.24	0.0717	0.0951	0.0254
2	1.3266	0.1393	0.655	0.0329	0.0152	38.92	0.0790	0.1260	0.0538
3	1.3215	0.1376	0.612	0.0331	0.0203	29.74	0.0929	0.1819	0.0483
4	1.1307	0.1227	0.663	0.0175	0.0239	40.60	0.0646	0.1943	0.0451
5	1.1286	0.1235	0.655	0.0177	0.0250	29.48	0.0731	0.2046	0.0371
6	1.1133	0.1236	0.636	0.0189	0.0262	30.80	0.0783	0.2155	0.0414
7	1.5361	0.1533	0.654	0.0310	0.0221	44.37	0.0792	0.1903	0.0624
8	1.5633	0.1558	0.662	0.0329	0.0198	37.19	0.0830	0.1757	0.0549
9	1.5490	0.1579	0.644	0.0355	0.0208	55.99	0.0834	0.1818	0.0831
10	1.4895	0.1499	0.594	0.0180	0.0430	34.16	0.1058	0.417	0.0640
11	1.4799	0.1513	0.563	0.0189	0.0473	32.48	0.1176	0.4782	0.0676
12	0.7595	0.0900	0.566	0.0267	0.0123	15.24	0.0827	0.1103	0.0209
13	0.7560	0.0912	0.547	0.0339	0.0074	40.90	0.0898	0.0667	0.0609
14	0.5515	0.0702	0.679	0.0216	0.00097	32.52	0.04136	0.0069	0.0217
15	0.5459	0.0709	0.652	0.0212	0.0035	32.28	0.0520	0.0260	0.0271
16	0.5242	0.0702	0.639	0.0233	0.0021	51.82	0.0537	0.0150	0.0448
23	1.0926	0.1481	0.441	0.0436	0.0392	41.35	0.1542	0.3540	0.1094
25	1.0960	0.1464	0.452	0.0481	0.0321	26.34	0.1487	0.3130	0.0672
26	1.0887	0.1448	0.446	0.0442	0.0361	28.19	0.1515	0.3610	0.0732
27	1.2924	0.1652	0.477	0.0657	0.0207	33.35	0.1480	0.1981	0.0861
28	1.3434	0.1658	0.471	0.0597	0.0281	27.07	0.1541	0.2710	0.0730
31	1.5393	0.1936	0.383	0.0723	0.0472	34.64	0.2210	0.5490	0.1361
33	0.7163	0.1105	0.516	0.0395	0.0140	28.07	0.0977	0.1043	0.0452
35	0.7103	0.1037	0.369	0.0407	0.0248	23.69	0.1594	0.2735	0.0623
36	0.7051	0.1095	0.309	0.0369	0.0388	29.91	0.1960	0.4861	0.0967
39	0.5108	0.0861	0.421	0.0382	0.1164	10.41	0.1143	0.0992	0.01912
40	0.5116	0.0868	0.411	0.0417	0.0094	25.85	0.1183	0.0815	0.0491

entrainment rate (table 1). This was to be expected since the thicker film would provide conditions for wave formation which would promote higher rates of entrainment.

The extraction of a liquid film through a porous sinter device is more difficult in the case of horizontal annular flow due to the presence of a thicker liquid film in the lower part of the tube. In addition large waves have been observed so that the liquid film may sometimes occupy more than one-half of the channel cross-section. These two effects may cause the liquid film to bridge the porous sinter in the lower part of the tube and allow some vapour, together with part of the entrained liquid, to be drawn off through a dry patch on the upper surface.

In these experiments it was unlikely that the porous sinter was operating under such adverse conditions. The calculated liquid film thickness is very small which precludes the formation of large waves. The amount of steam extracted along with the liquid film was determined from an energy balance on the heat exchanger, and any experimental data for which the rate of steam extraction was greater than 2 per cent of the total flow in the test section were rejected. In this calculation it was assumed that the liquid film formed by condensation was not undercooled since its resistance was negligible in comparison with the other surface resistances.

From studies of air–water systems it has been found that the exact condition of hydrodynamic equilibrium, in which the rate of deposition balances the rate of entrainment, is never reached even in very long tubes. It has been suggested (Hewitt & Hall-Taylor 1970) that the departures from hydrodynamic equilibrium may be more severe in systems in which condensation is occurring due to the changing conditions along the duct.

The combined effects of deposition and entrainment along a tube can be found from measurements of the liquid flow in the film and in the vapour core in the form of droplets. It has been shown that the deposition rate is given by $K_D C_E$ (Hewitt & Hall-Taylor 1970) where K_D is a mass transfer coefficient and C_E is the concentration of droplets in the vapour core. A value of 0.15 m/s has been found for K_D for an air–water system. At the present time very few measurement of the entrainment rate have been made and then only for an air–water system.

Hutchinson & Whalley (1972) assumed that hydrodynamic equilibrium may be approached provided that $L_{/D} > 150$ or if $P/[\mathrm{d}P/(\mathrm{d}Z)] > 20$ metres and selected their data from all their available experimental results accordingly. In the work being reported here annular flow started at the entrance to the precondenser section giving an $L_{/D}$ ratio at the test section exit of 210.

It was only possible to evaluate $P/[\mathrm{d}P/(\mathrm{d}Z)]$ for the test section and this was found to lie in the range 35–55 metres. The value for both the precondenser and test section together is likely to be far higher since the pressure drop along the 5.0 m long precondenser would be less than along the test section due to the thinner liquid film.

In these experiments the thickness of the liquid film on the tube wall increased along the duct due to condensation and led to higher rates of entrainment towards the exit. This increased the concentration of liquid in the core resulting in a higher rate of deposition. Thus the process may be regarded as being self-regulating in which a state of hydrodynamic equilibrium may be approached provided the previous conditions are satisfied.

Correlations of the type proposed by Hutchinson & Whalley (1972) Hughmark (1973) and Paleev & Filippovich (1966) have been chosen for the purpose of comparison. In the first case the data has been plotted (figure 3) in terms of $(\tau_i m)/\sigma$ and C_E the concentration of liquid in the vapour core. This implies that hydrodynamic equilibrium existed at the test section exit so that the rate of entrainment was directly proportional to the concentration of liquid in the vapour core. The curve approached a minimum value of $(\tau_i m)/\sigma$. Hewitt & Hall-Taylor (1970) have stated that, even at very high gas velocities, the

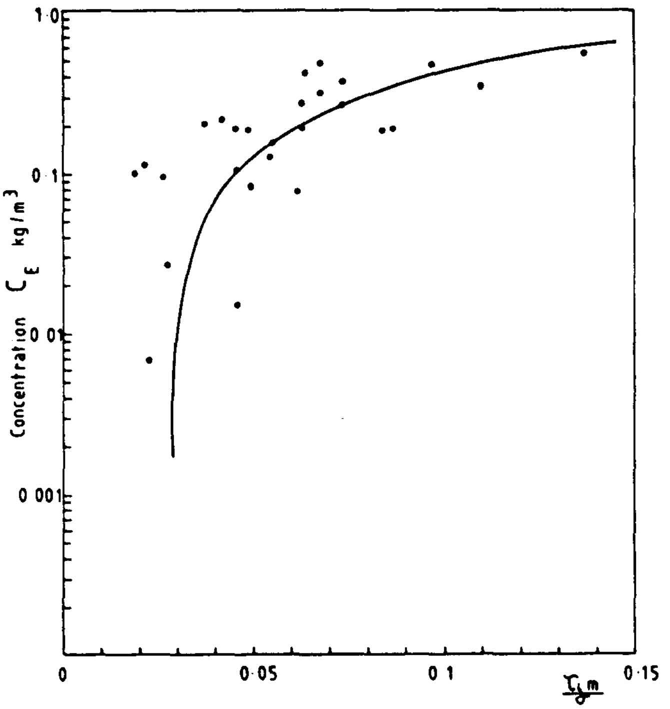

Figure 3. Entrainment correlation of Hutchinson & Whalley (1972).

fraction of liquid entrained can be zero. The interfacial shear stress was related to the vapour velocity. The formation of waves at the liquid–vapour interface was dependent on the vapour velocity and the liquid film thickness. These results implied that the combination of these two parameters needed to be large enough to overcome the surface tension effect at the liquid–vapour interface for the onset of entrainment. An equation of the form $C = b[(\tau_i m)/\sigma]^a$, where $b = 3.47 \times 10^{-4}$ and $a = -6.99 - 3.85 \log_{10}[(\tau_i m)/\sigma]$, was used to represent the results. The experimental data points exhibit some scatter around the general trend which may be due to the difficult nature of the liquid film flow rate measurements and the procedure used for calculating τ_i. However, although further work is required to accumulate more experimental data, these preliminary results offer some support for the use of the group $(\tau_i m)/\sigma$ to correlate the entrainment rate in a steam–water system.

A comparison with the correlations proposed by Hughmark and by Paleev and Fillippovich is shown in figures 4 and 5. The experimental results do not substantiate either of these correlations and entrainment occurred at a lower level of $y_G{}^+$ than the limiting value of 35 found by Hughmark.

Further work is currently being carried out to extend the range of measurements to include the liquid film thickness and the rate of droplet deposition for tubes of varying length.

CONCLUSIONS

Measurements of the liquid film flow rate in condensing steam–water annular flow have been made by withdrawing it through a porous sinter section. The accompanying entrained flow has been calculated from a knowledge of the heat transferred during the condensation process.

A method used for correlating entrainment data from air–water experiments has been applied to a system involving a phase change. The results available so far support the theory that entrainment ensues when the disturbance of the interface caused by the local shear stress is high enough to surmount the resisting surface tension. The evidence suggests

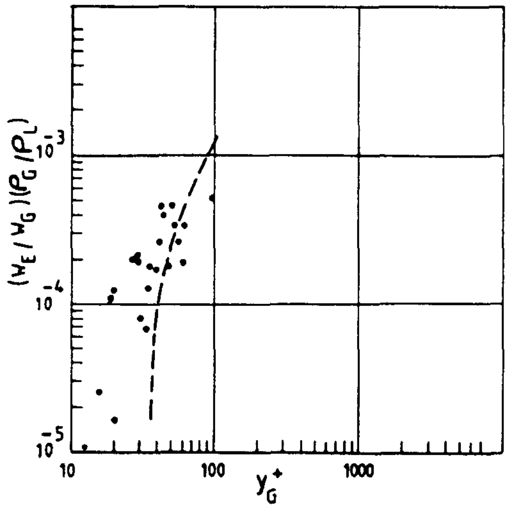

Figure 4. Entrainment correlation of Hughmark (1973).

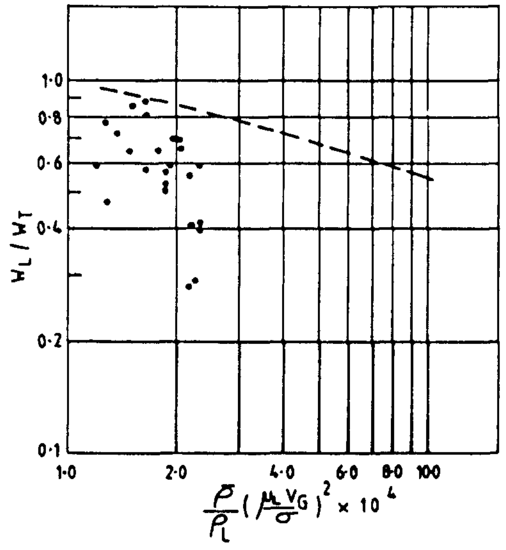

Figure 5. Entrainment correlation of Paleev & Filippovich (1966).

that conditions approaching hydrodynamic equilibrium may be reached in a system in which a phase change is occurring.

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