MEASUREMENT OF LIQUID ENTRAINMENT FROM A HORIZONTAL CYLINDRICAL VESSEL BY A FLOW OF AIR

A. A. Malinkovskii and B. V. Rossinskii

UDC 532.529.5

An empirical formula has been derived for the time needed for removal of a liquid from a horizontal cylindrical chamber by an air flow.

Various forms of equipment use droplet detachment from a liquid by a gas flow; this entrainment method occurs at a rate dependent on various factors, which often determine the correct and reliable operation of the equipment.

A qualitative description of entrainment is to be found in the literature, for instance, in [1, 2].

Here we report measurements on the entrainment of the liquid 1 from the horizontal cylinder (Fig. 1) by the air flow 2; the air is supplied through holes in the end wall, which lie above the level of the liquid. The air and droplets emerge from the chamber through a nozzle, at which a critical pressure difference is always maintained. We examined the effects of the physical and thermophysical parameters of the liquid on the entrainment, as well as the volume of the liquid, the gas parameters, and the chamber geometry. The tests were done with water, glycerol, tetrabromoethane, carbon tetrachloride, ethyl alcohol, and aqueous solutions of glycerol and ethanol. The temperature of the liquid was always 15-20°C. The air temperature varied from 20 to 700°C. The maximum air-flow rate was 4 kg/sec. The geometrical dimensions of the chamber and nozzle (Fig. 1) were as follows: D = (75-123) mm, l = (200-450) mm, d = (25-50) mm. The volumes of liquid V_l ranged from 0.1 liter to half the chamber volume. This was V_l = 2.5 liters for the largest chamber.

Fast transducers measured the chamber pressure, which was recorded by a loop oscillograph; Fig. 2 shows typical waveforms. The pressure rise during the entrainment period is due to partial blockage of the nozzle by the droplets. The pressure recording was accompanied by high-speed cinephotography. The film was compared with the oscillograms to establish that droplet entrainment begins when the pressure starts to rise, while one can assume that the chamber has been completely free from liquid when the pressure begins to fall (virtually exponentially). The difference between these two instants equals the time for the chamber to lose all its liquid by entrainment, and this is called the total entrainment time or clearing time τ (Fig. 2).

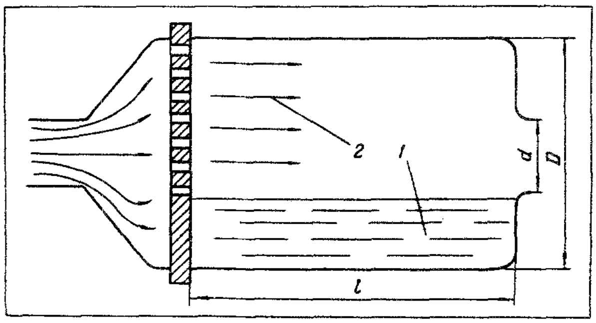

Fig. 1. The chamber.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 28, No. 1, pp. 108-112, January, 1975. Original article submitted November 13, 1973.

©1976 Plenum Publishing Corporation, 227 West 17th Street, New York, N.Y. 10011. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, microfilming, recording or otherwise, without written permission of the publisher. A copy of this article is available from the publisher for $15.00.

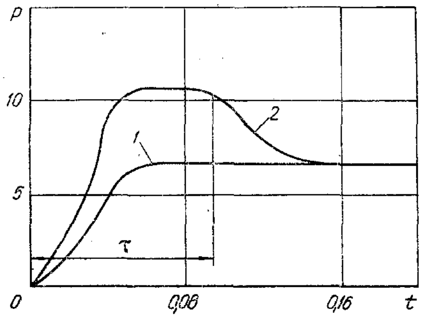

Fig. 2

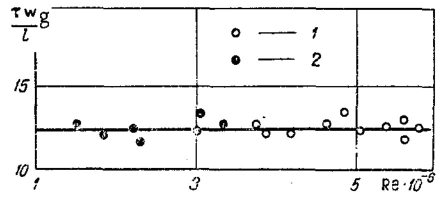

Fig. 3

Fig. 2. Pressure waveforms in chamber: 1) no liquid; 2) liquid transport.

Fig. 3. Relation of $\tau w_g/l$ to Re: 1) cold tests; 2) hot tests.

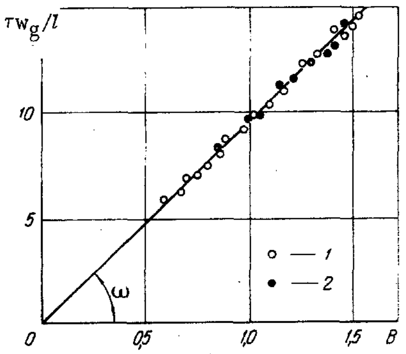

Fig. 4. Relation of $\tau w_g/l$ to B $= (\rho_l/\rho_g)^{1/3} (V_l/l^3)^{1/3} (l/D)^{1/3} \cdot (\rho_g W_g^2/P)^{1/6}$ for tan $\omega = 9.5$: 1) cold tests; 2) hot tests.

One purpose was to obtain a relationship in dimensionless terms to calculate τ from the parameters governing it. The latter include the following: ρ_l, μ_l, σ_l, V_l, ρ_g, μ_g, W_g, P, D, d, l; these defining parameters go with τ to form a system of 12 dimensional quantities, from which nine dimensionless combinations can be drawn up [3]:

$$1)\ \mathrm{Sh} = \frac{\tau W_g}{l};\quad 2)\ \mathrm{Re} = \frac{\rho_g D W_g}{\mu_g}\cdot\quad 3)\ \mathrm{We} = \frac{\rho_g W_g^2 D}{\sigma_l};$$

$$4)\ \mathrm{Eu} = \frac{P}{\rho_g W_g^2};\quad 5)\ \frac{\mu_l}{\mu_g};\quad 6)\ \frac{\rho_l}{\rho_g};\quad 7)\ \frac{V_l}{l^3};\quad 8)\ \frac{l}{D};\quad 9)\ \frac{d}{D}.$$

We found that d/D affects only the gas speed in the chamber W_g, with no other effect on the process; in other words, d/D is completely incorporated via the Euler number. Therefore, d/D was subsequently excluded from consideration. The ranges in the other 8 quantities in the other experiments were as follows:

$$\mathrm{Re} = \frac{\rho_g D W_g}{\mu_g} = 1.5\cdot 10^5 - 10^7;\quad \mathrm{We} = \frac{\rho_g W_g^2 D}{\sigma_l} = 1.7\cdot 10^3 - 4.5\cdot 10^5;\ \mathrm{Eu} = \frac{P}{\rho_g W_g^2} = 29 - 200;\quad \mu_l/\mu_g = 23 - 10^5;\quad \rho_l/\rho_g = 30 - 1500;\quad V_l/l^3 = 0.0011 \div 0.315;\quad l/D = 1.6 - 6;\ \mathrm{Sh} = \frac{\tau W_g}{l} = 5 - 18.$$

We found that the Weber number had no appreciable effect on the process by comparing the removal times for water, aqueous ethanol, and an OP-7 soap solution, whose surface tensions differed by more than a factor of two, while the other properties were similar, the experiments being conducted under identical conditions. An analogous conclusion may be drawn from the effect on Sh of μ_l/μ_g and Re. Figure 3 shows as an example the relation of $\tau W_g/l$ to Re, which was recorded with the other quantities constant. We varied the viscosity of the air via the temperature, while the viscosity of the liquid was varied by using water, glycerol, aqueous alcohol, and aqueous glycerol. For instance, the viscosity of water differed from that of glycerol by a factor of 1500. On the above basis, we may say that We, Re, and μ_l/μ_g have no effect on the process.

Therefore, on the various possible dimensionless quantities that might influence the transport rate in a cylindrical horizontal chamber, we have the dependent quantity $\tau W_g/l$ and the four controlling quantities ρ_l/ρ_g, l/D, V_l/l^3, and $P/\rho_g W_g^2$; here the following point must be noted. Since in this processing the parameters of the nonstationary process are best represented by their stationary values, we selected ρ_g and W_g from the condition that the liquid had been completely removed and the gas pressure P equalled the gas pressure in the chamber free from liquid (Fig. 2). The liquid volume V_l was taken as equal to the initial volume of liquid poured into the chamber.

The results from over 500 tests were processed by the methods of the theory of similarity and dimensions, and this gave the following equation:

$$\frac{\tau W_g}{l} = 9.5\left(\frac{\rho_l}{\rho_g}\right)^{1/3}\left(\frac{V_l}{l^3}\right)^{1/3}\left(\frac{l}{D}\right)^{1/3}\left(\frac{\rho_g W_g^2}{P}\right)^{1/6}. \quad (1)$$

Figure 4 shows the experimental results used to derive (1); only some of the measured values are shown here.

If we put $\rho_g W_g^2/P$ in the form W_g^2/RT_g and perform certain algebraic steps, we can put (1) in the form

$$\tau = 9.5\left(\frac{\rho_l V_l}{\rho_g W_g^2 \sqrt{RT_g}} \frac{l}{D}\right)^{1/3}. \quad (2)$$

Formula (2) allows us to determine the clearing time for air removing liquid from a horizontal cylindrical chamber; it shows that τ is dependent on the density and initial liquid volume, the dynamic head, and the work content of the gas, as well as on the chamber geometry.

NOTATION

ρ_l	is the density of liquid;
μ_l	is the viscosity of liquid;
σ_l	is the surface tension of liquid;
V_l	is the volume of liquid;
ρ_g	is the gas density;
μ_g	is the gas viscosity;
T_g	is the temperature of gas entering chamber;
R	is the gas constant;
W_g	is the gas velocity in chamber;
P	is the pressure in chamber;
τ	is the time of entrainment;
D	is the chamber diameter;
d	is the nozzle diameter;
I	is the chamber length;
Sh	is the Strouhal number;
Re	is the Reynolds number;
We	is the Weber number;
Eu	is the Euler number.

LITERATURE CITED

1. S. S. Kutateladze and M. A. Styrikovich, Hydraulics of Gas — Liquid Systems [in Russian], Gosénergoizdat (1958).
2. G. Wallis, One-Dimensional Two-Phase Flows, McGraw-Hill (1969).
3. L. I. Sedov, Similarity and Dimensional Methods in Mechanics [in Russian], Nauka (1972).