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EXPERIMENTAL STUDY OF THE ACCELERATION OF A LAYER OF LIQUID

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Measurements have been made on the basic dynamic parameters of the process during physical implementation under laboratory conditions.

There has long been an interest in methods of direct conversion of gas thermal energy to liquid kinetic energy in relation to the development or improvement of static devices for liquid transport in various engineering systems [1, 2]. The piston method of liquid acceleration may be used in such devices along with the injection and acceleration of the liquid in a two-phase flow [3-5]. In this method, the liquid is accelerated in individual batches, which are supplied to some channel in turn with the supply of compressed gas or steam, the result being a stratified (piston) flow with regions of liquid (pistons) alternating with regions of gas. In such a flow, the gas or steam can expand by expelling the liquid pistons into a region of lower pressure, where part of the internal energy of the thermodynamic working body is converted to kinetic energy in the liquid.

The basic hydrodynamic effects accompanying the acceleration of liquid pistons are analogous to the phenomena in the rise of large gas bubbles in a liquid [6]. For example [7], the phase interface (initially planar) in the accelerated ejection of a liquid from a channel by gas comes to take the form of a gas cavern entering the liquid with some characteristic velocity v, whose value is related to the other definitive parameters (liquid acceleration a and characteristic transverse dimension d of the channel) by the Froude equation:

$$v/\sqrt{ad} = \mathrm{Fr},$$

where Fr is some constant dependent on the shape of the cross section (Fr = 0.38 for a circular cross section [8]). Because the gas bubble enters the liquid, the part of the liquid around the gas is lost from the acceleration process. The rate of entry of the gas bubble into the liquid in essence defines the rate of disruption of the accelerated liquid layer. One assumes that the energy characteristics of the piston method of liquid acceleration will be largely determined by this effect.

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TABLE 1. Experimental Data on the Total Momentum of Jet I, Momentum I_p of Remaining Part of Piston, Speed of Liquid Front v_p, and Effective Piston Length l_p at the End of Acceleration in Relation to Initial Gas Pressure p_0

No.	p_0, abs. atm	I, kg·m/sec	I_p, kg·m/sec	v_p, m/sec	l_p, m	$\frac{d}{v}\sqrt{\frac{p_0}{\rho}}\times10^{-6}$	$\frac{I_p}{l_{pi}d\sqrt{p_0\rho}}$	$\frac{I}{l_{pi}d\sqrt{p_0\rho}}$
1	4,2	12,5	12,5	19,3	0,108	0,95	0,95	0,95
2	9,0	22,5	14,1	26,8	0,091	1,40	0,73	1,16
3	10,7	24,5	18,4	27,0	0,118	1,51	0,87	1,16
4	11,5	23,0	17,7	27,5	0,097	1,57	0,81	1,05
5	14,7	29,1	19,5	27,3	0,123	1,78	0,79	1,17
6	16,0	30,8	21,0	—	—	1,85	0,82	1,20
7	16,2	37,2	23,8	34,5	0,118	1,86	0,92	1,44
8	20,8	43,0	29,3	43,0	0,120	2,11	1,01	1,48
9	26,5	42,0	31,8	—	0,085	2,38	0,96	1,27
10	34,0	46,8	28,5	51,5	0,095	2,70	0,76	1,24

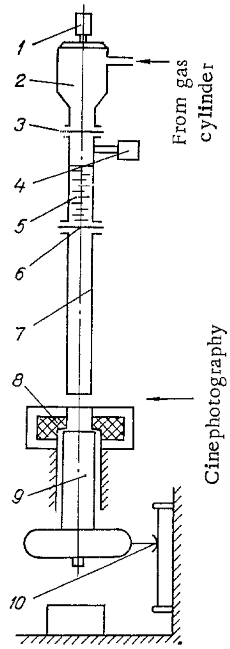

Fig. 1

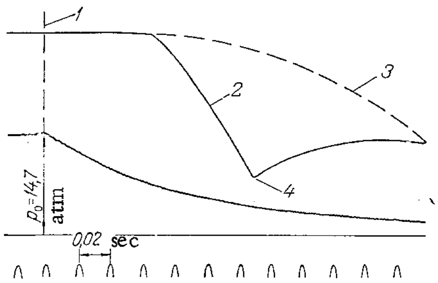

Fig. 2

Fig. 1. The apparatus: 1) pressure transducer in the gas accumulator; 2) gas accumulator; 3) diaphragm retaining compressed gas; 4) bellows contact indicator for instant of failure of diaphragm 3; 5) vessel containing liquid metal; 6) diaphragm retaining liquid metal; 7) acceleration nozzle; 8) electromagnetic holding trap; 9) ballistic trap for liquid jet to measure momentum; 10) slide wire displacement transducer.

Fig. 2. Waveforms in the movement of the ballistic trap for measuring liquid momentum: 1) initial motion of trap; 2) motion of trap in experiment; 3) free motion without liquid; 4) end of motion of trap.

The viscous interaction in the liquid will also have a marked effect on the characteristics, since this should not only accelerate disruption of the moving layer of liquid on account of the fall in velocity at the walls but there should also be a resistance force acting against the motion.

Here we present results on implementation of the piston method in order to elucidate some qualitative and quantitative characteristics. We examined the state of acceleration of a single liquid-metal piston in which appropriate choice of the initial piston length eliminated complete disruption within the acceleration section.

In meeting this condition, the basic characteristics of the device relevant to practical applications are the total momentum of the liquid jet leaving the acceleration nozzle, the momentum of the remaining continuous

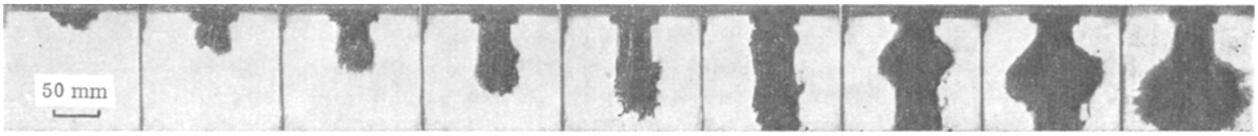

Fig. 3. Example of high-speed cinematography of the escape of liquid piston from the nozzle: 1250 frames/sec.

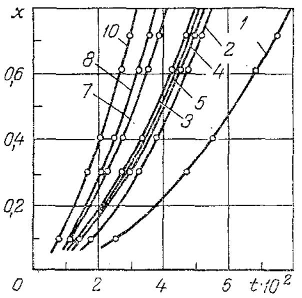

Fig. 4. Motion of the front of the liquid layer. The numbers on the curves are the sequence numbers of the experiments in Table 1; x, m; t, sec.

part of the piston at the exit from the nozzle, the speed of the front of the liquid piston at the end of the nozzle, and the extent of piston disruption during acceleration.

Figure 1 shows the scheme of an apparatus for examining the acceleration of a single liquid piston. The liquid was a triple alloy of 62% gallium, 25% indium, and tin with the following physical properties under normal conditions [9]: density $\rho = 6.4 \cdot 10^3$ kg/m^3, kinematic viscosity $\nu = 29 \cdot 10^{-8}$ m^2/sec, surface tension α = 0.658 N/m, and melting point 10.7°C. The working gas was argon with an initial temperature of 20°C. The volume of the compressed-gas accumulator (the initial volume of compressed gas) was $V_0 = 0.8 \cdot 10^{-3}$ m^3. The geometrical parameters of the acceleration nozzle (circular tube) were not varied and were as follows: length of acceleration part (from the front of the piston in the initial position to the end) 0.8 m, internal diameter 0.034 m. The initial length of the piston l_{pi} was 0.22 m in all the experiments. The temperature of the nozzle and of the liquid metal before the experiment was kept at 50°C.

In the initial state, the liquid-metal piston was in the position shown in Fig. 1; then gas was slowly admitted to the accumulator 2, and the pressure rose smoothly to the failure pressure of the diaphragm 3. The diaphragm 6 broke at almost the same instant as diaphragm 3, and the strength of this was less than that of diaphragm 3, and the liquid-metal piston began to be accelerated by the compressed gas. When diaphragm 3 ruptures, the contact indicator 4 operates and shorts out the solenoid 8, and the trap 9 used to measure the momentum acquired by the liquid during the acceleration begins to fall freely. During the free fall, the trap captures the main body of the liquid jet and therefore acquires additional momentum, which can be determined from the motion diagram. Device 9 provides for trapping the liquid without reflection of the jet.

To simplify the procedure for determining the momentum of the liquid, the mass of the falling trap should be large relative to the mass of liquid in order that one can neglect the change in the effective mass in the equation of motion of the trap. Then the equation may be put as

$$M\Delta u = (Mg - F_{fr})\Delta t + \Delta I, \tag{1}$$

where M is the mass of the trap; Δu, increment in the velocity; g, acceleration due to gravity; F_{fr}, frictional force of the falling trap on the guides ($Mg - F_{fr}$* is determined from the fall diagram without accelerating the liquid); and ΔI is the momentum communicated to the trap by the liquid in time Δt. As Δu is readily determined from the diagram, (1) allows one to find the momentum communicated to the trap with sufficient accuracy. Also, (1) shows that the instrument used to determine the momentum of the liquid is essentially a mechanical integrator and does not require calibration, which distinguishes it favorably from systems of differentiating type, e.g., ones that record the deformation of an elastic plate by the jet of liquid.

Figure 2 illustrates the method from the waveforms for the ballistic trap for run No. 5 in Table 1. For comparison, the broken line shows the free fall of the trap under gravity alone. We also show the pressure

* In most of the experiments, the $Mg - F_{fr}$ of (1) was negligible by comparison with ΔI.

curve in the gas accumulator, which indicates the instant of failure of diaphragm 3 and the start of expansion. This also corresponds to the start of movement of the trap, which moves in free fall until the liquid jet reaches it. The jet accelerates the trap appreciably, and therefore the curve deviates downwards. The tangent of the angle of deviation of the actual motion from the free fall is proportional to I_p in accordance with (1).

Analysis of the fall from (1) shows that the initial step in the momentum is followed by a monotone increase, which corresponds to trapping of the part of the liquid lost by the piston and flowing from the nozzle after the escape of the piston part, as was evident from high-speed cine photography, which showed that this liquid is present as a film on the wall and which may also occur in disperse form because the gas flow breaks up the film. The contribution from this part of the jet to the total momentum transferred to the trap was up to 40%.

High-speed cine photography was used to examine the explosion of the gas bubble after escape from the nozzle into the free space (Fig. 3). This also provided information on the speed of the front of the piston on exit from the nozzle. The speed and momentum of the remaining continuous part give the effective mass and the effective length of the piston at the end of acceleration. The speed was also determined from graphs relating the current coordinate of the front of the piston x to time (Fig. 4), which were recorded with induction transducers. These were thin circular coils mounted on the tube and uniformly distributed along it. These transducers worked at 1.1 kHz, which provided the necessary sensitivity and an adequate penetration depth for the electromagnetic field passing through the titanium wall of the nozzle into the liquid metal flow.

Table 1 gives results on the total momentum of the jet I, the momentum of the remaining part of the piston I_p, the speed of the front v_p, and the effective length l_p at the end of the nozzle in a series of experiments in which the failure pressure of diaphragm 3 was varied, i.e., the initial pressure p_0 in the acceleration. Also, we give for each experiment the calculated value of an analog of the Reynolds number for a liquid piston Re = $\frac{d}{\nu}\sqrt{\frac{p_0}{\rho}}$ and the normalized momentum of the piston part at the end of the nozzle together with the total momentum. These data show that the normalized momentum of the piston part at the end tends to be constant within this range of Reynolds number, in spite of the variation in the velocity of the liquid, with fluctuations of the order of the error in determining the momentum. A similar conclusion can be drawn on the disruption of the liquid piston during acceleration. This leads one to hope that further improvement in the liquid velocity would be available by raising the initial pressure of the thermodynamic working body.

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