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Experimental investigation into the flow of liquid film under saturated steam condition on a vibrating surface

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Abstract—This paper investigates the flow of a thin liquid film on the lower surface of a horizontal rectangular duct subjected to forced vibration. The duct had a cross-section of 40×30 mm^2 and a length of 1000 mm. The instantaneous film thickness recorded by electrode-type film thickness gauges for various conditions of steam flow and quality was used for the analysis of the mean characteristics of the thin liquid film. Statistical analysis was carried out to understand the effect of vibration on the wave structure of the film. The results show that, in the low-frequency zone ($f < 100$ Hz), which corresponds to the maximum amplitude of vibration, the thickness of the liquid film decreases and the film surface is disturbed. The presence of a surface active agent in the steam helps to stabilize the wavyness of the surface.

INTRODUCTION

Liquid flows in the form of a film on the surface of saturated steam turbines, moisture separator-reheaters, steam extraction lines and in many heat exchangers used in the power and process industries. The service life and efficiency of these depend, to a large extent, on the flow stability and interfacial condition of the wavy film. The wavy film plays an important role in mass and heat transfer. The presence of a very thin liquid film on the surface of equipment changes the characteristics of two-phase flow and causes a loss of energy in the steam (gaseous) phase. Experimental data on the flow of liquid films reported by various investigators are mainly limited to the study of air–water two-phase flow, where the liquid film was artificially formed. In practical situations, wherever saturated steam flow occurs, the process of formation of a liquid film is very complicated due to continuous deposition of droplets, the entrainment of liquid from the wavy surface, and the subsequent break-up of the entrained liquid into droplets. The absence of a sophisticated apparatus to measure the instantaneous film thickness makes any attempt to study the flow of liquid films quite complicated. Of the different techniques available, two techniques, one based on film conductivity measurement and the other on film capacitance measurement, have found wide application. These methods do not disturb the two-phase flow. In the reported work, a special apparatus based on film conductivity measurement was developed. It has advanced features for the correction of physical properties of liquid due to the presence of impurities and the variation of liquid temperature which always occur under real operating conditions. This improves the accuracy of the measurement of liquid film parameters.

In most of the cases involving saturated steam flow, the film surface is covered with a complicated wave structure. The waves are characterised by parameters like the mean film thickness ($\langle\delta\rangle$), the dimensions of crests and troughs, the phase velocity of the film, the wave frequency and the probability density $P(\delta)$. Extensive experimental work has been carried out on air–water two-phase flow. The mean film thickness depends mainly on Re_L. The gas steam velocity influences the film thickness and also defines the wave structure of the liquid film. Experimental results for film characteristics like $\langle\delta\rangle$, V_L, $P(\delta)$ and the wave frequency of a liquid film have been reported in ref. [1]. The effect of gas dynamic parameters on the flow of films in horizontal and vertical ducts has been the focus of attention of two-phase flow specialists for several years, and different flow regimes for horizontal and vertical flows have been identified for air–water two-phase flow [2, 3]. Figure 1 [2] shows the flow pattern for a horizontal rectangular duct. The flow regime for saturated steam flow resembles the flow pattern in the E regime, where deposition of droplets and break-up of film take place simultaneously. Most of the investigators were concerned with the study of a liquid film on steady surfaces. In actual operating

NOMENCLATURE

A	amplitude [mm]
b	width of liquid film (duct) [m]
f	frequency of vibration [Hz]
K	kurtosis
P	probability density
Q	volumetric flow [m^3 s^{-1}]
Re_L	Reynolds number, $V_L\langle\delta\rangle/\nu$ or Q/b
S	skewness
V	velocity [m s^{-1}]
y	moisture content [%].

Greek symbols

δ	film thickness [microns]
$\bar{\delta}$	$\delta_f/\delta_{f=0}$
σ	standard deviation
$\bar{\sigma}$	$\sigma_f/\sigma_{f=0}$
ν	kinematic viscosity [m^2 s^{-1}]
$\langle\ \rangle$	mean value.

Subscripts

f	frequency
g	gas
L	liquid
s	steam.

conditions, vibration caused due to numerous known or unknown factors is unavoidable. The process of the formation and flow of a liquid film in ducts with saturated steam flow is a very complicated physical process, and it is further complicated by an imposed external vibration. Hardly any experimental/theoretical data are available on the flow of a liquid film on vibrating surfaces.

EXPERIMENTAL ARRANGEMENT

The essential features of the experimental set-up are shown in Fig. 2. The saturated steam duct which forms the test section was mounted at the exhaust of an experimental turbine. The test section is rectangular with a cross-section of 40 × 30 mm^2 and 1000 mm long. The wet steam is supplied to the test section from the extraction line of the steam turbine of a gas-fired plant. In order to attain different degrees of wetness, steam was throttled and feedwater was sprayed on, which provided a high degree of moisture content (up to $y = 18\%$). The experiments were conducted for a steam velocity (V_s) in the range of 46–118 m s^{-1}. The liquid film thickness was measured on the lower surface of the test section. A thin metallic sheet of 1.5 mm thickness formed the lower surface of the test section. It was subjected to forced vibration by an electromagnetic vibrator. To determine the values of Re_L a slot was provided throughout the width of the lower surface near the exit of the test section. The slot was connected to a condenser to suck out the liquid. The ranges of variables covered in the present investigations are:

$$V_s = 46\text{–}118\,\mathrm{m\,s^{-1}}$$
$$Re_L = 16\text{–}116$$
$$y = 7\text{–}18\%$$
$$A = 0\text{–}1.5\,\mathrm{mm}$$
$$f = 0\text{–}1000\,\mathrm{Hz}.$$

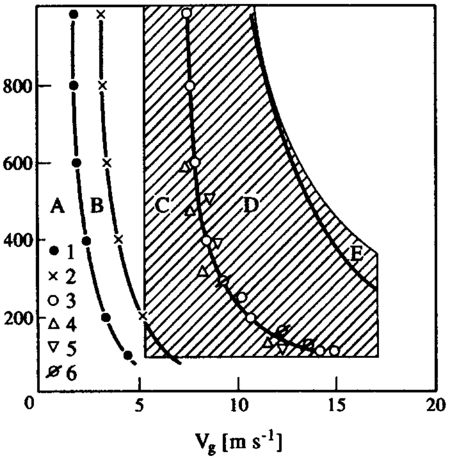

Fig. 1. Liquid film wave regimes as reported by different authors [2]: (1)–(3) P. V. Besfamilni, 1986; (4) T. J. Hanratty, 1964; (5) T. J. Hanratty, 1957; (6) S. V. Alekseenko, 1973; (A) smooth surface, (B) two-dimensional waves, (C) three-dimensional waves, (D) prebreak-up regimes, (E) film break-up.

The Reynolds numbers for the liquid film calculated for different flow regimes are given in Table 1.

Three pairs of film thickness gauges were mounted on a thin metallic sheet. The film thickness gauges were mounted at locations where the effect of vibration on the liquid film was expected to be maximum. The amplitude of the vibrations was measured for the complete range of frequency variation ($f = 0$–1000 Hz). The film thickness gauges were pre-calibrated. The complete data set for the experimental arrangement is reported in ref. [4]. The signals from the gauges were fed to the film thickness apparatus. The output from the film thickness apparatus was connected to an oscilloscope. The output from the oscilloscope was digitized and analysed on a PC for the characteristics of the liquid film.

EXPERIMENTAL RESULTS AND DISCUSSION

The lower portion of the duct was subjected to forced vibration in the following ranges: $A \leqslant 1.5$ mm

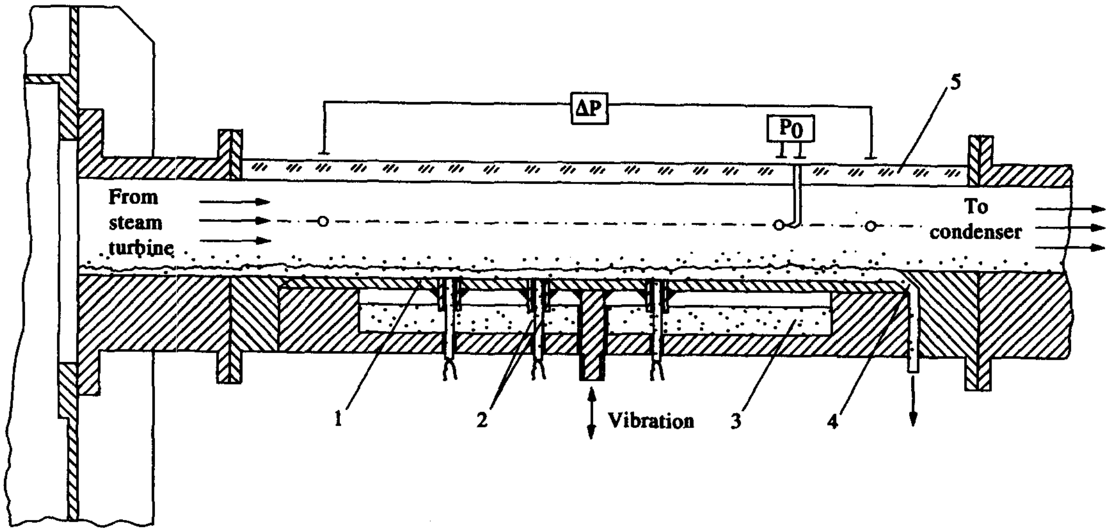

Fig. 2. Experimental arrangement of saturated steam duct.

Table 1. Reynolds numbers for the liquid film

y [%]	V_s [m s^{-1}] 46	118
7	66	16
13	96	24
18	116	32

at $f \leqslant 50$ Hz and $A \leqslant 0.15$ mm at $100 \leqslant f \leqslant 1000$ Hz. The visual observation as well as measurement by film thickness gauges indicated that, in the low-moisture zone ($y < 3\%$), the surface is covered by irregular rivulets. A stable liquid film was observed on the surface when the moisture content was increased to 5%. Figure 3 gives the dependence of the film thickness $\langle\delta\rangle$ for a steady surface and the dimensionless film thickness $\langle\bar{\delta}\rangle$ for a vibrating surface on the steam velocity for a constant y (=13%). Similarly Fig. 4 gives the dependence of $\langle\delta\rangle$ and $\langle\bar{\delta}\rangle$ on the moisture content of the steam (y) for a constant V_s of 68 m s^{-1}. The trend of decreasing values of film thickness with increasing V_s in Fig. 3 is clear and is in agreement with previous work. The decrease in film thickness is due to an increase in the intensity of the break-up of the film with velocity rather than deposition of droplets on the surface. For the range of velocities studied, $\langle\delta\rangle$ decreases by almost 35% when the surface is not subjected to an external disturbance. For any particular velocity, external vibrations further decrease the liquid film thickness. For the range of frequencies and velocities studied, the liquid film is more sensitive to the dynamic disturbance caused by the flow of steam itself than to external vibration. Nevertheless, film thickness decreases with the appearance of external vibration in all of the cases. The influence of the moisture content on $\langle\delta\rangle$ and vibration as a parameter in Fig. 4 has shown that $\langle\bar{\delta}\rangle$ similarly decreases on a vibrating surface. Both Figs. 3 and 4 indicate that a thin film is more sensitive to vibration than a thicker film with a higher Re_L.

Analysis of the results of the investigation has shown that vibration generates ripples on the surface of the liquid film, and thus increases the interfacial area for energy transfer. The ripples along with the

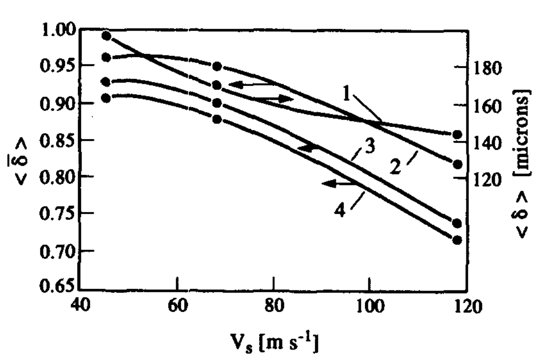

Fig. 3. Film thickness vs steam velocity at $y = 13\%$: (1) $f = 0$, (2) $f = 100$ Hz, (3) $f = 50$ Hz, (4) $f = 25$ Hz.

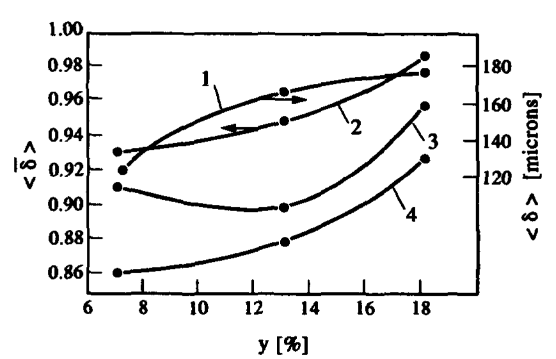

Fig. 4. Film thickness vs moisture content at $V_s = 68$ m s^{-1}: (1) $f = 0$, (2) $f = 100$ Hz, (3) $f = 50$ Hz, (4) $f = 25$ Hz.

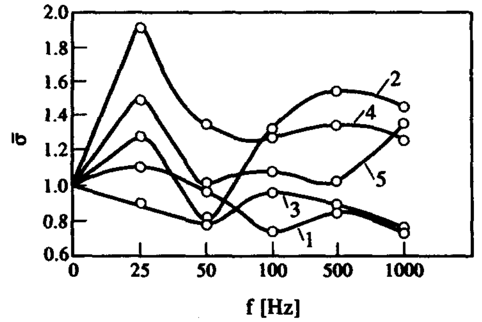

Fig. 5. Relative standard deviation vs frequency: (1) $V_s = 68$ m s^{-1}, $y = 18\%$; (2) $V_s = 68$ m s^{-1}, $y = 13\%$; (3) $V_s = 118$ m s^{-1}, $y = 13\%$; (4) $V_s = 68$ m s^{-1}, $y = 7\%$; (5) $V_s = 118$ m s^{-1}, $y = 7\%$.

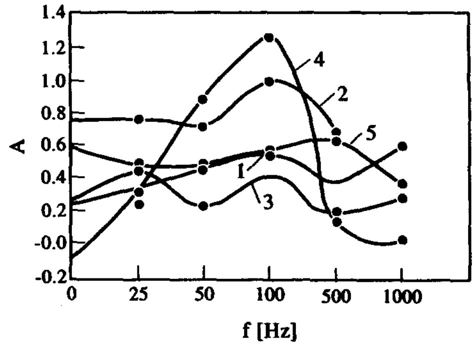

Fig. 6. Skewness vs frequency. Legends same as for Fig. 5.

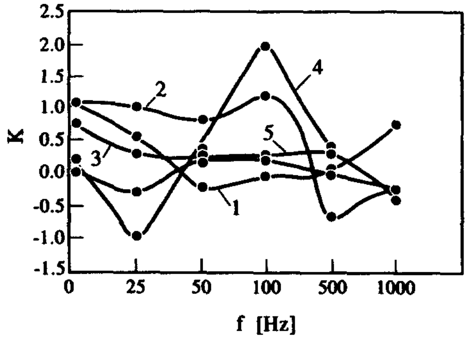

Fig. 7. Kurtosis vs frequency. Legends same as for Fig. 5.

large and the medium waves present at the steam–water interface transport a greater mass of liquid. This causes an accelerated movement of the liquid mass and a thinning of the liquid film for a particular film Reynolds number.

In order to study the role of vibration in wave formation and its effect on wave structure, recordings of instantaneous film thickness were used to define statistical characteristics.

Theoretical modelling of the wavy surface of the two-phase interface cannot describe the actual shapes that exist on the interface. Attempts have been made by Chu and Dukler [5] to study the randomness of the film through the probability or spectral density of the film thickness for large waves in vertical air–water flows. Here, for saturated steam flow, the structure of the steam–liquid interface is described by statistical parameters like the standard deviation (σ), skewness (S) and kurtosis (K). The standard deviations in dimensionless form ($\bar{\sigma}$) for different values of the moisture content and steam velocity are given in Fig. 5. The data show that the liquid film flow is generally not very sensitive to vibration and the maximum disturbance is noticed at $f = 25$ Hz, where the amplitude of vibration is the highest. Moreover, it can also be noticed that, at a higher steam velocity, $V_s = 118$ m s^{-1}, and moisture content, $y = 13$ and 18%, the effect of vibration is the least. Although the standard deviation is very widely used for many practical purposes, it does not give full information about the wave structure. More information can be obtained from Figs. 6 and 7. When all three parameters, viz. σ, S and K, are simultaneously taken into account, the following general characteristics can be observed:

(1) The values of S in most of the cases are positive, which implies that symmetry in probability density curves is often disturbed because of deep troughs, and the distribution curve moves to the side with increasing film thickness.

(2) Kurtosis which defines the sharpness of the distribution curve decreases in most of the cases, and the wave structure is uniform in nature. The appearance of a rare large wave occurs at a high value of S and a small value of K. As an example of this, points on curve 4 (Figs. 6 and 7) corresponding to $f = 50$ and 100 Hz can be cited.

These data show that, on the basis of these parameters, a simplified wave model in the interface can be proposed for given values of $\langle \delta \rangle$, the maximum and minimum amplitudes of the film ($A_{\text{max.}}$ and $A_{\text{min.}}$), σ, S and K for different flow conditions.

(3) With an increase in steam velocity, the wave amplitude decreases and the instantaneous film thickness band is widened. In the low-velocity area, high values of K are observed, which suggests the appearance of a large number of medium waves.

The presence of a surface active agent (SAA) in two-phase flow, especially in a steam turbine, where film flow is accompanied by high turbulence, plays an important role. It was found that, with the injection of an SAA (like $C_{18}H_{37}NH_2$) in saturated steam with a concentration of 5 mg kg^{-1} (sufficient from the point of view of erosion and corrosion protection for structural steel under saturated steam flow condition [6], the film thickness and the wavyness of the surface decrease. The values of σ, S and K also decrease on a vibrating surface, which means that the distribution of the film thickness comes close to the Gausian distribution curve. Figure 8 shows the change in $\langle \delta \rangle$ under different conditions of flow and vibration.

CONCLUSIONS

Experimental results on the flow of a liquid film under two-phase flow conditions show that the effect

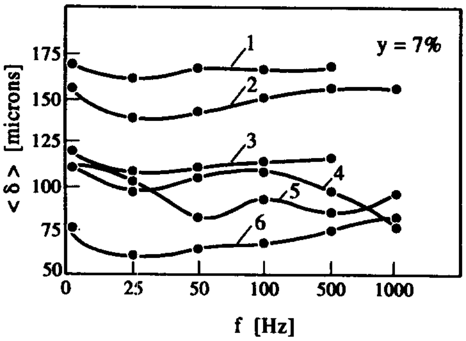

Fig. 8. Effect of vibration on mean film thickness ($\langle\delta\rangle$) : (1), (3), (5) saturated steam; (2), (4), (6) saturated steam with SAA; (1), (2) $V_s = 46\ \mathrm{m\ s^{-1}}$; (3), (4) $V_s = 68\ \mathrm{m\ s^{-1}}$; (5), (6) $V_s = 118\ \mathrm{m\ s^{-1}}$.

of forced vibration on the mean film thickness is not very large compared to the dynamic disturbance at the steam–water interface. The characteristics of the liquid film are not disturbed by forced vibration at high frequency ($f > 100$ Hz). Such vibrations need not be considered during the design stage of the elements of turbines and other equipment where liquid film flow is encountered. The present study also indicates that the film parameters are more sensitive to the amplitude of the vibration than to the frequency for the range studied. The presence of an SAA influences the wave structure of the film and acts as a stabilising factor. As a result, the steam–water interface becomes less wavy.

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