Experimental study of high-speed gas-film flows in curvilinear channels with drop injection of liquid

S E Shcheklein and E M Bochkareva

1 Ural Federal University, Department of Nuclear Power Plants and Renewable Energy Sources, 620002 Yekaterinburg, st. Mira 19, Russia
2 Kutateladze Institute of Thermophysics, 630090 Novosibirsk, 1 Lavrentiev Ave., Russia

Abstract. The paper investigates the local thickness distribution of a wall liquid film in a curvilinear channel. The research technique on experimental water–air stand with a curvilinear working channel is described. The results of measurements of the local thickness of the liquid film on the upper and lower walls of the channel for two flow velocities are obtained at various flow rates.

1. Introduction
The use of a wet-steam technological cycle in modern nuclear power plants leads to the appearance and movement of a droplet and drop-film water-vapor flows in many elements of the circuit [1–3]. The presence of droplet moisture in high-speed steam flows and film flows on the internal surfaces of pipelines and equipment leads to an increase in the hydraulic resistance of the tract and deteriorating performance characteristics of the circuit [4, 5]. The phenomenon of erosive wear of the internal surfaces of pipelines and equipment with curvilinear profile is of special importance in the conditions of long-term operation. The presence of a radial flow of droplet moisture leads, in particular, to intensive erosion of the bends and turns of the pipelines.

Up to day, the local distribution of moisture along the length and section of the channel has not been sufficiently studied. Such information helps to determine the working conditions of curvilinear channels with dispersion-film wet-steam flows and to develop the methods for reducing erosion wear and removing moisture. One of the most important characteristic of the moisture distribution is the local thickness of the wall film of liquid in the curvilinear channel [6–9].

Data on local film thicknesses allow identifying the places of accumulation and optimal selection of film moisture, determining the zones of the most intense dropping of moisture on the walls of the channel and, consequently, possible zones of erosive wear [10, 11].

2. Experimental setup and methodology of research
The studies were carried out on a water-air setup (figure 1) with the air velocity $W_g$ range from 0 to 60 ms$^{-1}$ and water flow rates $G_l$ from 10 to 150 mls$^{-1}$. Working channel with a turning radius of 0.28 m had a rectangular section of 100x50 mm.

The supply and distribution of the liquid was realized with the aid of a high-pressure nozzle by the ejection method (figure 2) at an accelerating air pressure of 1 to 2 MPa, which provided dispersion of water into droplets with a modal size of 50 μm.
Figure 1. Scheme of the experimental setup.
1 – blower; 2 – control valve; 3 – membrane; 4 – thermometers; 5 – flow straightener; 6 – inlet region; 7 – nozzle unit; 8 – manometer; 6 – tachometric liquid flow rate sensor; 10 – filter; 11 – feed pump; 12 – film distribution units; 13 – channel; 14 – damper valves; 15 – bypass; 16 – separator; 17 – control valves; 18 – flowmeters; 19 – pump; 20 – tank; 21 – damper valve; 22 – compressor; 23 – control valve.

Figure 2. Scheme of the nozzle unit construction.
1 – channel body; 2 – channel flange; 3 – inlet pipes for dispersed air–water mixture; 4 – bolted assembly; 5 – water inlet; 6 – water chamber body; 7 – water chamber flange; 8 – air chamber flange; 9 – air inlet; 10 – manometer fitting; 11 – air chamber body; 12 – nozzle.

Figure 3. Scheme and numbers of measurement points for the local thickness of the liquid film.
The local thicknesses of the liquid films were measured using AC conductivity sensors (carrier frequency of 20 kHz), polled by an electronic comparator with a frequency of 100 Hz. The measurement results were recorded by a data collection and processing computer system. The design of the sensors allowed for the hardware integration of the film thickness in the measurement section. The arrangement of the sensors in the curvilinear channel is shown in figure 3. The same numerals show the section numbers in which the film thickness measurements were made.

3. Results and discussion

Figure 4 shows the measurement results of the local thickness of the liquid film for small (figure 4a) and large (figure 4b) airflow velocities with different volumetric flow rates (in the form of droplets). With an airflow velocity of more than 30 ms\(^{-1}\), the film thickness on the upper channel wall becomes larger (figure 4b) than on the bottom wall at all volumetric flow rates.

Figure 5 shows the measurement results of the local thickness of the liquid film for small (figure 5a) and large (figure 5b) liquid volumetric flow rate with different airflow velocities. As can be seen from figure 5, when spraying water at the channel inlet, precipitation of droplets of dispersed moisture occurs at any initial flow rates of the liquid volumetric rates and air velocities. The coordinates along the length of the film formation channel of the greatest thickness are significantly different for low air velocities (less than 20 ms\(^{-1}\)) and large (more than 40 ms\(^{-1}\)). In the first case, the deposition is maximum at the channel inlet, in the second – at the channel outlet.

**Figure 4.** The thickness of the liquid film on the channel walls for water flow rate \(G_l = 23\) mls\(^{-1}\) and 102 mls\(^{-1}\) for airflow velocity \(W_g = 20\) ms\(^{-1}\) (a) and 60 ms\(^{-1}\) (b).

**Figure 5.** Thickness of liquid film on the channel walls for airflow velocity \(W_g = 20\) ms\(^{-1}\) and 60 ms\(^{-1}\) for water flow rate \(G_l = 23\) mls\(^{-1}\) (a) and 102 mls\(^{-1}\) (b).
The presented results show that as the flow rate of the supplied liquid grows, the thickness of the film increases both on the bottom and the top walls of the channel. An increase in the air flow rate in contrast reduces the liquid film thickness. An important phenomenon is the inversion of film flow at high air velocities, consisting in the film redistribution from the bottom wall of the channel to the top one.

A generalization of the investigation results allows determining the limiting velocity of the dispersed flow at which the film flow inversion effect occurs – $W_g > 30 \text{ m s}^{-1}$ at all concentrations of moisture in the flow. The physical patterns of motion and distribution of moisture in the flow of a dispersed flow in a curvilinear channel are shown in figure 6.

The results of investigations in the pre-inverting flow area correspond to the theoretical model of I. A. Fuchs [12]. The observed phenomenon of film flow inversion in the flow velocity area $W_g > 30 \text{ m s}^{-1}$ requires further theoretical studies. However, already obtained results allow developing optimal technical devices for removing moisture from the elements of power equipment in order to reduce its erosion wear.

4. Conclusion
As a result of the research, a database of experimental data on precipitation of droplets of dispersed moisture in a wide range of liquid volumetric rates and air velocities has been obtained. Data have been also obtained on the places of accumulation of film moisture at spraying water in the curvilinear channel. The analysis of the film formation along the channel length has been carried out. Data obtained on local film thicknesses allow identifying places of accumulation and optimal selection of film moisture, determining the zones of the most intense dropping of moisture on the walls of the channel and, consequently, possible zones of erosive wear. A generalization of the investigation results served to determine the limiting velocity of the dispersed flow at which the film flow inversion effect occurs – $W_g > 30 \text{ m s}^{-1}$ at all concentrations of moisture in the flow. Note that an important phenomenon is the inversion of film flow at high air velocities, consisting in the film redistribution from the bottom wall of the channel to the top one. When designing the moisture sampling devices for high-velocity flows in curvilinear channels, it is advisable to perform a circular moisture sampling.

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