Using Flow Swirlers to Enhance Heat Transfer in Apparatuses of Wet Regeneration of Waste-Gases Heat

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Abstract. The paper presents results of experimental study of the effect of air-droplet flow swirling on evaporation of moisture contained in the flow. The tests were conducted in a round 30 mm tube within the range of Reynolds number (15-50)10³ at the wall heat flux ranged from 14 to 23 kW/m² and water-spraying density 10-20 g/(m s). It was demonstrated that the swirling inserts enhance droplet deposition from the flow core to the wall and recover the evaporated liquid film at a length equal to several tube calibers. Followed by dried zones appearing at the wall again. This is due to the processes of liquid film rupture and liquid entrainment accompanying liquid deposition enhancement. The overall effect of the flow swirling appeared to be less effective than it was anticipated.

1. Introduction
Waste-gases heat regeneration is widely used in gas-turbine cycles. A degree of waste heat regeneration can be increased if it is applied in combination with water injection in the compressed air downstream of the compressor, i.e. at the regenerator inlet [1].

Weight and size characteristics of the regenerator with water injection depend to a great extent on a rate of the injected liquid phase evaporation. When this happens, the liquid phase can exist as a film flowing along the channel wall, and as droplets containing in the air-vapor core of the flow [2]. Heat removal from the wall, which is heated by the turbine waste gases, can be carried out by two ways, respectively. The first way is immediate evaporation of the liquid film on the wall, while the second one is a multistage heat transfer from the dried wall to the air-vapor-droplet flow and then from that flow to the droplets contained in it with subsequent droplet evaporation. Due to its multistage nature the second way is less intense.

Due to a gas-dynamic impact of the air-vapor core two- and three-dimension waves are formed on the wall-adjacent liquid film surface. Droplets are stripped-off from the wave crests, and a considerable part of moisture is entrained to the flow core. Films flowing over the wall disintegrate into several jets (rivulets). Part of the entrained droplets returns to the wall [3-5]. Therefore, while designing “wet regenerator”, an intention to maximally concentrate moisture on the walls of a shell-and-tube apparatus is quite natural. This applies for modern plate-type apparatuses, as well.

For studying liquid film behavior on heated walls and thermal state of the tube elements under the conditions, which are typical of the GTU with wet regeneration, series of corresponding experiments was conducted at OIVT RAS. The results obtained are briefly presented in [6].
2. Experimental results for smooth tubes
The schematic diagram of the experimental installation is shown in figure 1. The test section of the installation is made of stainless steel pipe with an inner diameter of 30 mm, a wall thickness of 1.5 mm and a length of 2 m. The pipe was heated by direct adjustable alternating current; the length of the heating section was 1.83 m. The main part of the experiments was conducted when cold distilled water was supplied to the inlet of the test section through a centrifugal nozzle, which ensured the formation of a uniform liquid film on the wall at the inlet to the channel. The flow of water irrigating the wall could change. The inlet to the working section was also supplied with the drained air of the required flow rate and temperature. A discharge of the water vapor and air mixture was carried out into the atmosphere. Residual (unevaporated) liquid was collected into the measuring tank. Wall temperature was measured by chromel-alumel thermocouples welded to the wall along its two generatrixes. From outside, the tube had thermal insulation. Details of the installation and experimental technique are described in [6].

![Figure 1. Installation layout.](image)

The results of the conducted experiments confirmed a complex nature of heat transfer and evaporation of the liquid films flowing inside the heated tube at the conditions of concurrent gas flow, when an interaction of the following processes takes place: liquid film evaporation, film nucleate boiling, droplet evaporation in the gas flow, and convective heat transfer to the air from the dried and superheated segments of the tube.

It was confirmed that the wavy film flowing on the tube wall is broken-up into individual rivulets due to complex dynamic impact of air flow, thermocapillary forces, and liquid boiling. Water washing of individual zones of the heating surface is nonuniform in space and aperiodic in time. Spots covered by liquid film are intermitted with dry patches.

An intense liquid entrainment from the film is observed, as well. A considerable part of the injected water turns into the air-droplet flow and evaporates according to low-efficient two-stage pattern of heat transfer from the heated wall.

As a result, the following problem had to be solved. It was necessary to experimentally check whether there is a possibility to return entrained moisture to the wall and ensure efficient liquid film evaporation. Below, we describe the experimental results of liquid film evaporation with a presence of air-droplet flow swirlers, which must provide flow swirling and return droplet to the wall due to centrifugal forces.
3. Results of experiments with swirling devices

Geometrical characteristics of the test section remained the same as in study [6]. Petal-shaped swirlers were installed at a pitch s=200 mm (s/d=6.67) along the tube length starting from a section located at 150 mm from the beginning of heated zone.

In total, 60 experiments were conducted. Air mass flow rate varied from 13 to 27 kg/(m²s) (Re_{air}=(15-50)10^3), air temperature at the test section inlet changed from 15 to 200°C, wall spraying rate was 10-20 g/(m² s), heat flow rate at the wall was 14.4-23 kW/m², film Reynolds number at the tube inlet was 40-100.

Figure 2 shows wall temperature distributions in the smooth tube and in the tube with swirlers during dry air heating without water injection.

Figure 2. Wall temperature distribution along the test section.

We can see that a presence of swirlers considerably enhance convective heat transfer. Heat transfer coefficient in the zone downstream the cross section, in which a swirler is installed (swirler positions are marked by point lines in the figure), is increased by 4-4.5 times and reaches a level of about 250 W/(m²K). We can also see that the effect of the swirler rather quickly decreases along the flow, and at a distance of approximately 5 calibers from the swirler, heat transfer coefficient is by 30% lower; while wall temperature is higher, respectively. The change in the wall temperature along the tube is saw-tooth like. In all cases, the noticeable effect of swirlers on the downstream flow is evident.

Figure 3 demonstrates the effect of swirlers on the wall temperature in the case of water injection at the test section inlet. We can see that in the zones immediately adjacent to the places, where swirlers are installed, the wall temperature is below 100°C. This fact points out the existence of the liquid film and its evaporation at these places, which is characterized by a high heat transfer coefficient. However, this pattern changes rather quickly and already in few calibers downstream the tube wall temperature has a value, which is typical of the case of convective heat transfer to the air at a presence of swirlers (see figure 2). Such a situation is typical of all conducted experiments. Thus, swirlers return liquid to the wall, but the process of hydrodynamic destabilization of the flow is far from ceasing. On the contrast, destabilization apparently increases, and the wall becomes dry again, although at a somewhat lower temperature as compared to the smooth tube case. For comparison, figure 4 reproduces the wall
temperature distribution typical of the smooth tubes. We see fast (at $H > 800$ mm) wall temperature rise to 240-260°C and retaining this level over the entire section to the tube end.

![Figure 3](image1.png)

**Figure 3.** Effect of flow swirling on the wall temperature.

$G_{\text{air}}=20$ g/s, $t_{\text{air}}=100$°C, $G_{\text{wat}}=1.8$ g/s, $t_{\text{wat}}=15$°C, $N_{e}=4077$ W, $q_{w}=22100$ W/m². Horizontal point lines show swirlers position.

Figure 5 represents the experimental data on the water flow rate at the test section outlet $G''_{\text{wat}}$ at small air velocities ($G_{\text{air}}=10$g/s). One can see that at the air temperatures 16 and 100°C, the degree of moisture evaporation is essentially the same at both the presence and absence of swirlers. At the air temperature at the channel inlet 200°C, when a linear velocity of the flow increases by 1.5 times due to temperature rise, certain difference in the moisture evaporation degree can be seen (points 5 and 6).

An increase in the efficiency of evaporation due to the air flow rate rise is shown in figure 6.

![Figure 4](image2.png)

**Figure 4.** Wall temperature change along the channel length.

$G_{\text{air}}=15$ g/s, $t_{\text{air}}=100$°C, $G_{\text{wat}}=1.8$ g/s, $t_{\text{wat}}=15$°C, $q_{w}=21400$ W/m² (smooth tubes).

![Figure 5](image3.png)

**Figure 5.** Comparison of the experimental data on the moisture flow rate at the test section outlet: with (4, 5, 6) and without (1, 2, 3) flow swirling. $G_{\text{air}}=10$ g/s, $G_{\text{wat}}=1.0$ g/s, air temperature at the inlet $t'_{\text{air}}=16$°C (points 1 and 4), 100°C (points 2 and 5) and 200°C (points 3 and 6).

![Figure 6](image4.png)

**Figure 6.** Effect of flow swirling on liquid entrainment at different air mass flow rates $t_{\text{air}}=100$°C, $G_{\text{wat}}=1.0$ g/s, $t_{\text{wat}}=15$°C, $G_{\text{air}}$ g/s: 1 – 10, 2 – 15, 3 – 20.
At the same time, we must point out that in all cases analyzed flow swirling did not radically change the situation with moisture evaporation, i.e. a considerable part of the injected liquid evaporated according to the two-stage scheme “heated wall – air – droplets”. However, an increase in the convective heat transfer coefficient from the wall to the air (up to 250 W/(m²K)) provided an acceptable level of the total thermal resistance for this process. As a result, heat transfer area of the simulated regenerator will be determined primarily by the heat transfer intensity of the GTU waste gases to the apparatus wall.

Simultaneous enhancement of the processes of the droplet deposition on the heating wall and moisture entrainment from the liquid film is quite understandable in physical sense because both the effects are resulted from one and the same reason. Up to present time this fact has not been directly pointed out in the scientific literature, although it is very important from the engineering standpoint because of the negative effect (an increased moisture entrainment) levels the positive one (enhancement of the evaporation surface spraying).

In the experiments, the data on hydraulic resistance of the channel with flow swirlers were obtained as well (figure 7). The relative increase in the hydraulic resistance was by 4-5 times higher as compared to the case without swirlers.

![Figure 7. Dependence of pressure drop on the air flow rate at different initial temperatures](image)

At the same time, inserts, which swirl vapor-droplet flow increase droplet deposition from flow core on the heating wall and recover an evaporating liquid film on the wall surface at a tube section of several calibers long. The limited length of the section, where the liquid film is recovered, is associated with an enhancement of droplet entrainment by the swirled flow and repeated formation of dry spots.

Flow swirlers significantly enhance convective heat transfer to the dry sections thus considerably reducing the total thermal resistance of the two-stage process of heat transfer from the heating wall to evaporating droplets. Under these conditions, a resulting area of heat transfer surface of the GTU waste-gases wet-regeneration heat exchanger will be determined by the least intense process of heat transfer from waste gases to the regenerator wall.

Hydraulic resistance of the studied channel with swirling inserts is 4-5 times greater than that of the smooth channel.

The experimental data obtained do not give comprehensive information, which is necessary for reliable design of the apparatuses of wet regeneration of GTU waste gases. In particular, it would be interesting to obtain similar data on heat transfer and hydraulic resistance for plate heat exchangers with porous coating at the heated working medium side and with heat transfer intensifiers from the waste gases side.
5. References

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