Heat transfer in a tube with sudden expansion and additional miniturbulator

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Abstract. The process of interaction of two separated flows of various scales in a tube with a sudden expansion is investigated. It has been determined that an additional turbulizing element in the form of a small diaphragm leads to dramatic changes in the structure of the recirculation zone in the channel behind a step, shift in the flow attachment point, and, accordingly, redistribution of heat and mass transfer coefficients. The approach of a mini-turbulizer to the separation point increases the size of recirculation zone and heat transfer intensity. An increase in the height of a mini-turbulizer affects similarly the characteristics of a separated flow.

1. Introduction
Currently, the task of heat and energy conservation is among the priority areas for the development of science and technology. Introduction of energy-saving technologies in the industry requires the creation of more efficient energy equipment with increased reliability. One of the important aspects is the problem of passive intensification of heat transfer by organizing flow separation and possibility of controlling the heat and mass transfer processes. Passive heat transfer intensifiers are easy to manufacture and highly reliable. Their wide use in heat power equipment - heat exchangers, nuclear reactors, combustion chambers, cooling channels of gas turbine units - requires deep understanding of the flow structure and heat and mass transfer with varying geometry of a streamlined obstacle and thermo-gas-dynamic parameters of the external flow. Therefore, one of the urgent tasks of aerodynamics and heat and mass transfer is the development of the methods for controlling the characteristics of heat and mass transfer. Interest in this problem is constantly growing [1-4], however, due to the complexity and multifactorial nature of the phenomenon, it remains not fully understood.

The passive control methods based on the use of additional turbulizing elements of substantially smaller geometrical scales than the main obstacle, causing flow separation, are the most acceptable from a practical point of view. The separated flow is controlled by introducing an additional vortex layer into the separation zone, which leads to drastic changes in the structure of the recirculation zone, displacement of the flow attachment point, and, accordingly, redistribution of heat and mass transfer coefficients [4]. The search for the optimal size of the vortex generators, their location in combination with the scale of the main separated flow is a complex multi-parameter problem.

2. Flow scheme and calculation method
In this study, the calculated area was a tube with a sudden expansion. To cause an additional disturbance of the boundary layer, a flat annular diaphragm was installed in the small-diameter tube (Fig. 1). When varying the location of the additional turbulizing element, the following cases were considered: 1) without additional disturbance (the basic version without a diaphragm); 2) installing the
diaphragm immediately before separation, $S_g = 0$ mm; 3) installing the diaphragm 50 mm before separation, $S_g/h_g = 5$; 4) installing the diaphragm 100 m before separation, $S_g/h_g = 10$; 5) installing the diaphragm 150 mm before separation, $S_g/h_g = 15$. The Reynolds number determined by the parameters of the inlet tube section was $Re = 6700$. The calculations were performed when the tube was heated after a sudden expansion under the boundary condition $q_w = \text{const}$. At the tube inlet, the temperature and velocity profiles were uniform.

When varying the height of the additional turbulizing element, parameter $h_g$ took the following values: 0; 2.5; 5; 10; 15; 20; and 25 mm. In this case, its location was fixed: $S_g = 100$ mm. The Reynolds number determined by the parameters of the inlet tube section was $Re = 133300$.

The computational domain was discretized by the grid with tetragonal cells, whose total number varied depending on geometrical sizes of the separated area. The calculation grid was nonuniform, thickening was performed equally towards all solid surfaces, such as tube walls and diaphragm. The computational domain included 240 000 – 280 000 nodes.

The boundary conditions at the tube inlet were characterized by uniform velocity profile, turbulence intensity calculated by formula \[ I = 0.16 \left( Re_D \right)^{1/8} \] [5], and constant air temperature $T = 283K$. At the outlet boundary, downstream, zero derivatives normal to the boundary were specified for all sought quantities, which corresponded to the free boundary condition. The thermal boundary conditions on the tube wall corresponded to heat flux constancy $q_w = \text{const}$. The $q_w$ value was selected so that the temperature difference between the wall and air did not exceed $\Delta T \sim 40^\circ$, and the flow conditions were close to isothermal.

The calculations are carried out in the framework of the model of incompressible liquid based on the system of stationary Navier-Stokes and energy equations, Reynolds averaged (RANS). The main tool for the study is the universal calculation complex FLUENT. The problem statement is two-dimensional; the flow is stationary and axisymmetrical. The turbulence model $k-\omega$ SST is chosen in [6], as the most appropriate for calculation of turbulent separated flows [7]. The previous studies of the authors [8, 9, 10] prove also that for the models, implemented in the given set, the results obtained with application of the mentioned model are the best to match the physics of the given flow type.

3. Calculation results

3.1. The effect of additional vortex-forming element location on separation, attachment and further development of the flow.

The streamlines (vectors) and distributions of the longitudinal velocity component (color) behind a sudden expansion are shown in Fig. 2a in the absence of additional disturbance, case 1. Immediately after the sudden expansion, a recirculation zone, characterized by the return flows and a high degree of turbulence, is observed. This is followed by the attachment area and the region of new boundary layer development. The flow pattern in the region of sudden expansion in the presence of an additional disturbance located directly in front of the separation point (case 2) is shown in Fig. 2 b). The recirculation zone increases almost two times. With moving the diaphragm away from the separation point towards the main flow (Fig. 2 c), case 5), formation of the return flow zone immediately behind a small obstacle and reduction in the length of recirculation zone of the main separated flow are observed.

Figure 1. Geometry of the round channel with a sudden expansion in the presence of an additional turbulizer before separation. Scheme of the computational domain.
The relative lengths of the heat transfer maximum coordinate $x_{\text{max}}$, $\text{Nu}_{\text{max}}$ values, and lengths of recirculation zone $x_R$ for all cases considered are compared in Fig. 3 for fixed values $h/R=0.4$ and $h_g/R=0.1$. It can be noted that all these values decrease as the diaphragm moves away from the step.

The greatest influence of diaphragm location is observed for the coordinate of heat transfer maximum $x_{\text{max}}/x_{\text{max},0}$, and its coordinate does not coincide with the point of flow attachment and is located much further downstream. The value of maximum heat transfer coefficient undergoes the weakest changes. It can be noted that the attachment point shifts downstream as the diaphragm approaches the step edge. In this case, the highest velocity gradients in the shear layer are also observed if the diaphragm is mounted immediately in front of the flow separation point. This leads to a greater extension of the recirculation zone and heat transfer intensification.

Distribution of local values of the Nusselt number shown in Fig. 4 indicates a fundamentally different character of distribution of local heat transfer coefficients depending on the location of a vortex-forming diaphragm. For the usual flow separation without a diaphragm, distribution has a pronounced maximum with subsequent relaxation of the flow to the developed one. If there is a diaphragm, starting from the area of flow attachment, there is a rather extended “plateau” with an almost constant heat transfer coefficient. As it follows from Fig. 4, integral heat transfer calculated over a tube section with a length of $0 <X/h< 25\div30$, where intensified heat transfer is observed, will significantly exceed its value without a vortex-forming diaphragm. At that, the Nu values are the greater, the closer to the step edge an obstacle is mounted. Thus, it can be assumed that heat transfer increases due to the additional effect of a turbulized wake from the diaphragm on the structure of separated flow behind a step or sudden expansion of the tube. There is an increase in the size of recirculation zone and the speed of flow rotation in it.

The data presented in Fig. 5 testify to the cardinal effect of pre-separation turbulentization on aerodynamic characteristics and, accordingly, wall friction. The level of negative tangential stresses in the recirculation zone increases as the diaphragm approaches the point of boundary layer separation. In this case, the level of integral hydraulic losses caused only by wall friction will decrease with introduction

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**Figure 2.** Flow pattern in the area of sudden tube expansion with variation in location of the additional turbulizing element (coordinates in meters).

**Figure 3.** Relative coordinates of the attachment point, maximum heat transfer coefficient and its location when varying the position of a turbulizing diaphragm.

**Figure 4.** Distribution of Nusselt numbers on the wall after a sudden expansion.
of a turbulizing wake into the recirculation zone. However, the question of total hydraulic losses remains open, since the pressure gradients in the conditions under consideration can play a decisive role.

3.2. The effect of the size of an additional vortex-forming element on separation, attachment and further development of the flow.

When varying the height of the additional turbulizing element, parameter $h_g$ took the following values: 0; 2.5; 5; 10; 15; 20; and 25 mm. In this case its location was fixed: $S_g = 100$ mm. The Reynolds number determined by the parameters of the inlet tube section was $Re = 133,300$. The streamlines (vectors) and distributions of the longitudinal velocity component (color) in the region of a sudden expansion with varying heights of the additional turbulizer are shown in Fig. 6. Immediately after a sudden expansion, a recirculation zone, characterized by the return flows and a high degree of turbulence, is observed. This is followed by the attachment area and the region of new boundary layer development.

The flow pattern in the region of sudden expansion in the presence of an additional turbulizer with a height of 5 mm is shown in Fig. 6 a). With increasing diaphragm height, $h_g = 10$ mm (Fig. 6 b)) and $h_g = 20$ mm (Fig. 6 c)) the recirculation zone behind the step increases significantly. Not only formation of a zone of return flows directly behind a small obstacle, but also its active interaction with the vortex zone of the main separated flow is observed.

The relative lengths of the heat transfer maximum coordinate, the values of this maximum, as well as the lengths of the recirculation zone for a variable-height diaphragm are compared in Fig. 7. The height of the additional vortex-forming element was varied within $0 \div 0.2 R$, while its position was fixed ($S_g/R = 1$).

As it can be seen from Fig. 4, an increase in the height of the additional turbulizer leads to a growth of a separation bubble, an increase in the level of heat transfer on the wall behind the step, and also to a shift in the position of heat transfer maximum downstream. It should be noted that the relative coordinate of $N_{u_{max}}$...
behaves nonmonotonously. Perhaps, this is due to flow attachment directly on the edge of a sudden tube expansion.

Conclusions
It has been determined that an additional turbulizing element in the form of a small diaphragm leads to dramatic changes in the structure of the recirculation zone in the channel behind a step, shift in the flow attachment point, and, accordingly, redistribution of heat and mass transfer coefficients.

The approach of a mini-turbulizer to the separation point increases the size of recirculation zone and heat transfer intensity. An increase in the height of a mini-turbulizer affects similarly the characteristics of a separated flow.

On the whole, this problem implies many unexplored questions, especially from the experimental point of view. In particular, this refers to the influence of the geometric scale of a turbulizer as compared with the size of the main separated element, Reynolds number of the flow, etc. However, the first data of numerical experiment indicate significant potential possibilities of such a method for controlling heat and mass transfer.

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