Heat transfer behind a sudden expansion in a round tube with variation of the expansion ratio

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Abstract. The results of a numerical study of the influence of a step height on the flow structure and turbulent heat transfer in the zone of flow separation, attachment and relaxation are presented. The range of Reynolds numbers is $Re_D = 6.7 \cdot 10^3 - 13.3 \cdot 10^4$. The degree of tube expansion varies within $ER = (D_2/D_1)^2 = 1.085 ÷ 4$. In the work will show how exactly the ratio of tube expansion affects hydrodynamics and heat transfer in the separation area. When increasing ER the separation area lengthens and becomes more extensive: from 5 to 12 step heights (5h - 12h). Heat transfer is not so intensive, $Nu_{max}$ decreases by the factor of 2.5. The coordinate of the maximum heat transfer $Nu_{max}$ moves downstream. Comparison the calculation results with the experimental data of other authors is presented. A correlation formula allowing calculation of the separated flow with consideration of the degree of tube expansion is presented as generalization of data obtained.

1. Introduction

Separated flows are among the most common, and simultaneously, the most difficult-to-study movements of a real fluid. Separation of a liquid or gas flow is one of characteristic properties of a viscous flow and a very important and complex phenomenon. Separated flows followed by flow attachment are found in many technical applications. Flow attachment can cause a significant change in the local heat transfer coefficient, as well as a significant increase in total heat transfer. From this point of view, turbulent separated flows have attracted close attention of researchers for a long time due to their extreme practical importance [1–12]. So, separation control can improve operation of gas turbines, increase heat transfer in heat exchangers, etc. Data on the flow conditions in the attachment region and subsequent development of the attached boundary layer are of particular interest for various engineering applications.

The flow in a tube with sudden expansion is one of the simplest types of separated flows. Despite this, there are still many poorly studied and contradictory aspects of this problem. The point is that the mechanism of turbulent flow separation in a confined channel is a complex and multifactorial process. In [13], the authors emphasize several basic parameters that affect flow separation, its further development and attachment: 1 - the state of the boundary layer under separation; 2 - thickness of the boundary layer before separation; 3 - the value of turbulence in the external undisturbed flow; 4 - longitudinal pressure gradient; 5 - the degree of channel expansion.

The current study deals with the effect of the expansion degree on dynamic characteristics of the flow and local heat transfer in a turbulent flow. With a change in the diameter of the outlet section, the step height changes as well. As compared with the studies available in the literature, this work is of interest in terms of systematic changes in the studied parameter, comparison of dependences obtained at different Reynolds numbers, as well as the possibility to study in more detail the processes occurring in the separated flow.
2. Scheme of computational region, boundary conditions
In the current study, a two-dimensional formulation of the problem for an axisymmetric flow is considered. The calculation area is schematically shown in Fig. 1. The tube diameter after expansion $D_2$ was changed from 125 mm to 240 mm, the diameter of the inlet section was fixed at $d = 120$ mm. Thus, the step height $h$ was changed as follows: 2.5, 5, 10, 20, 30, 40, and 60 mm.

To study the effect of the expansion degree on the turbulent separated flow in the tube, several values of this parameter were chosen. The corresponding values of the expansion degree $ER = (D_2/D_1)^2$ were: 1.085, 1.174, 1.361, 1.778, 2.25, 2.778, and 4.

The tube length after expansion was 1600 mm, which was not enough to stabilize the disturbed flow, especially for high steps. In this situation, we considered the case of separated flow in the tube section, right after the perturbation. This was interesting because here the separation zone has a rather large extent and the scale of the entire recirculation region is high as compared to the general geometry of the channel. This allowed a more detailed study of the processes occurring in the separated flow. The Reynolds number in a numerical experiment varied in the range of $Re_{D1} = u \cdot d/\nu = 6.7 \cdot 10^3 \div 1.3 \cdot 10^5$.

The $k-\omega$ SST turbulence model [14] was chosen as the most acceptable for calculating separated flows.

The computational grid was inhomogeneous; it was thickened equally to all solid surfaces, both to the tube walls and to the step surface. The total number of nodes of the computational grid varied from $110 \times 500$ to $340 \times 500$ depending on the size of the separation region. The average value of $Y^+$ lied in the interval from 1.2 to 1.4. Greater thickening of the grid towards the wall ($Y^+ < 1$) led to a significant decrease in the rate of convergence, while the result gave a difference of no more than 3%. The thickening coefficient was 1.08, which ensured smooth changes in the cell sizes. In all calculations, we applied the second-order accuracy scheme.

Boundary conditions at the inlet were as follows: power-law velocity profile with $n = 1/7$, degree of turbulence $I = 0.16 \cdot (Re_\theta)^{1/4}$, constant air temperature of $10^\circ$C. Boundary conditions at the outlet: free boundary condition (flow area where the effect of sudden expansion does not work). Thermal boundary conditions on the walls were as follows: constant heat flux on the wall behind a sudden expansion and no heat flux on the step wall and inlet tube wall. In this flow regime, there were no changes in the thermophysical properties; therefore, this was not taken into account in calculations.

3. Effect of the tube expansion degree on the dynamic characteristics of the flow
As it can be seen in Fig. 2, an increase in the degree of expansion increases rarefaction in the vortex zone and enlarges this zone noticeably. The recirculation zone is located under the separated shear layer and is characterized by a high intensity of turbulence. The length of the region of return flows is from 5 to 12 step heights (Fig. 3) and depends weakly on the Reynolds number at a small degree of expansion, but for large values of $D_2/D_1$ they almost coincide [9]. One of the main values characterizing the separated flow is the coordinate of the attachment point $x_r$. Due to this coordinate, it is possible to judge the length of the recirculation area and indirectly estimate the maximum velocity of the reverse liquid movement. Special attention is paid to the construction of the correlation dependence of $x_r$ on the studied parameter, both in experiments and calculations. The calculated data are compared with the experimental results obtained by other authors in Fig. 3. The calculation shows that the coordinate of the attachment point depends weakly on the Reynolds number, therefore, the data are presented only for $Re = 133300$. When the degree of expansion increases, a substantial monotonic increase in the length of
recirculation zone is observed. In the region of small expansions, there is an agreement with the experiment, and then the calculation gives overestimated $x_r/h$ values.

4. Effect of the degree of tube expansion on thermal characteristics

In the near-wall region of the recirculation zone, the heat flux normal to the surface is small as compared with longitudinal transfer. That is, heat from the wall is removed by the return flow, which after a half-turn, carries it to the boundary with the shear layer and transfers it to the latter. The local heat transfer coefficients in the recirculation region are higher than in the undisturbed flow, which indicates significant heat transfer on the wall.

Distributions of the local heat transfer coefficient on the wall behind a step for $Re = 133300$ are shown in Fig. 4. A noticeable effect of the boundary layer is visible, but the general pattern of a decrease in the heat transfer intensity with an increase in the expansion degree remains unchanged. The same analogy is observed in the results for other Reynolds numbers considered in the framework of this study. The tendency to a decrease in the maximum value of heat transfer depending on the pressure coefficient is clearly shown in Fig. 8. Indeed, the smaller the step height, the closer the region of increased turbulent pulsations, which intensify heat transfer, to the surface. These effects increase with increasing Reynolds number.

Let us consider heat transfer processes in the separated flow behind the steps of 2.5 mm, 10 mm, and 40 mm height. Temperature profiles in six cross-sections of the expanded tube are shown in Fig. 5. Cross-sections $x/h = 1, 4, 9$ are located in the zone of the return flow, and $x/h = 15, 25, 40$ are in the relaxation region.

The greatest thermal resistance occurs near the wall. The cross-section $x/h = 1$ is located in the so-called stagnant zone with weak mixing of the flows due to the low rotation speed of this vortex structure. Here, a greater thermal pressure is observed, both in the thin near-wall layer and beyond it.
Temperature profiles show that the greatest temperature head across the channel is observed in a thin near-wall layer. Heat transfer from the wall is determined by the intensity of turbulent mixing in the near-wall region. Moving upstream from the attachment area, the near-wall layer grows, becoming thicker as approaching the middle of the recirculation zone. The thickening of this layer causes a decrease in the heat transfer coefficient, which reaches its minimum in a vicinity of the secondary separation. In the corner zone, the intensity of temperature pulsations is maximal.

![Figure 5. Temperature profiles in several cross-sections of the tube after a sudden expansion: a) case for $h=2.5$ mm; b) case for $h=10$ mm; c) case for $h=40$ mm.](image)

Despite a relatively wide variation in the expansion degree, the average values of Nu in the region from the expansion to the attachment point for different Reynolds numbers are well generalized by the following dependence (Fig. 6): $Nu_{sr} = 0.11 \cdot Re_r^{0.67}$, which can be used in engineering calculations.

![Figure 6. Generalization of data for average heat transfer values.](image)
Conclusions

A series of studies was carried out using the ANSYS Fluent software package. The results showed how exactly the ratio of tube expansion affects hydrodynamics and heat transfer in the separation area. When increasing $ER = (D/d)^2$ from 1.085 to 4, the following changes occur.

- The separation area lengthens and becomes more extensive: from 5 to 12 step heights ($5h - 12h$).
- Heat transfer is not so intensive, $\text{Nu}_{\text{max}}$ decreases by the factor of 2.5. The coordinate of the maximum heat transfer $\text{Nu}_{\text{max}}$ moves downstream.

A correlation formula allowing calculation of the separated flow with consideration of the degree of tube expansion is presented as generalization of data obtained. This formula can be used in engineering calculations.

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