The influence of the shape and the orientation angle of the tabs on heat transfer in a separated region behind a backward-facing step

V I Terekhov¹², A Yu Dyachenko¹²*, V L Zhdanov³ and Ya J Smulsky¹

¹Institute of Thermophysics SB RAS, Novosibirsk, 630058, Russia
²Novosibirsk State Technical University, Novosibirsk, 630073, Russia
³Luikov Heat and Mass Transfer Institute, Minsk, 220072, Belarus

*E-mail: dyachenko@yandex.ru

Abstract. The influence of the shape, location and inclination angle of the tabs on heat transfer in the separation region behind the backward-facing step at the Reynolds number Re = 4000 has been investigated. The used tabs were rectangular and triangular in shape and had the same height of 6 mm. Their transverse spacing and the angle of attack varied. The presence of tabs approached the area of the maximum heat transfer to the step, and at that rectangular tabs were more effective due to the increase in the cross-sectional area. The smallest and the largest angles of attack reduced the maximum heat transfer, and the greatest heat transfer was observed for tabs installed either perpendicular to the flow or at angle 110º.

1. Introduction

The problem of heat and mass transfer in separated flows behind a backward-facing step has now become classical, but an interest in such study remains owing to the lack of knowledge of the full three-dimensional flow field and complex heat transfer. The use of effective methods of heat exchange control in separated flows allows solving several urgent problems at once: improving the efficiency of thermal-hydraulic equipment, upgrading the existing devices, and searching for new methods of heat transfer enhancement. One of the simplest and cheapest ways to control separation behind the ledge is passive; it is characterized by high reliability and simplicity but is not free from shortcomings and requires an increase in power to pump the coolant.

With this method of flow control, additional vortex-forming elements, namely, transverse ribs, vortex generators, etc. are used. Installed before the separation point, they intensify the mixing layer and destroy the stagnant zone. The selection of the optimal form and location of the barrier for a particular case is the most difficult stage of such a problem. Two-dimensional barriers lead to global flow restructuring, while vortex generators (tabs) cause a smaller change due to their size; however, the longitudinal vortices induced by them significantly affect the recirculation region behind the ledge [1]. The influence of the height, location and spacing of these tabs with a rectangular shape on heat transfer behind the ledge was studied in [2]. This paper considers two types of tabs located on the ledge boundary (rectangular and triangular) at varying angles of attack, which continues and develops the research of authors of [2].
2. Experimental setup and procedure

The experiments were carried out in a channel of the 1 m length with a rectangular cross section of 20×150 mm (Fig. 1). The channel is made of 10 mm thick textolite. At a distance of 600 mm from the channel inlet, there was a back-facing step with constant height \( H = 10 \) mm. On the lower wall of the channel behind the back-facing step, a thermal section (model) with the length of 400 mm was located. A heater strip of aluminum foil with the thickness of 50 μm was glued to the textolite layer; it ensured a constant heat flux on the heat-exchanging surface. To reduce heat losses on the outer surface of the textolite sheet, a layer of expanded polystyrene 20 mm thick was glued. Along the central line of the heated surface, 80 chromel-coppel thermocouples were mounted under the heater strip. Thermocouples are needed to identify thermograms obtained by a thermal imager. The distances between adjacent thermocouples were different: near the back-facing step, they were 2.5 mm, and at the end of the model, they were 20 mm. To evaluate heat leakage on the outer surface of the textolite plate, three thermocouples were mounted into the model. When the data processing, the radiation losses by black painted surface of the model under study were taken into account.

The local heat transfer coefficient was calculated by formula

\[
\frac{h}{\lambda} = \frac{q}{(T_w - T_0)}
\]

where \( q \) is the heat flux on the heated wall; \( T_w \) and \( T_0 \) are the wall and flow temperatures in the channel in front of the step, respectively. The Nusselt number was calculated using the following formula:

\[
Nu = \frac{hH}{\lambda}
\]

where \( h \) is heat transfer coefficient; \( \lambda \) is air heat conductivity, determined by the airflow temperature. The maximal uncertainty of coefficient measurement in this experiment did not exceed 5 %.

![Figure 1. The setup scheme.](image)

Vortex generators with a height \( \Delta = 6 \) mm and a thickness \( e = 0.6 \) mm, attached to the step boundary, were made of steel. The distance between tabs \( P \) varied from 25 to 50 mm. The angle between the ledge plane and the tab \( \alpha \) varied from 45 to 135. The tabs of rectangular 6*6 mm and isosceles triangular shape with the height of 6 mm were studied. The Reynolds number \( Re = U H/\nu \), calculated from the step height \( H \) and the average speed \( U \), was equal to \( Re = 4000 \). The average flow temperature was \( 21 \pm 1^\circ C \). At a distance of 25 \( H \) from the inlet, the flow was stable, and the velocity profile was close to the power one with an exponent of \( n \approx 1/7 \).

3. Result and discussion

The results of thermographic visualization of the temperature field in the region of the separated flow interaction with the channel wall are demonstrated in Fig. 2. It shows data for the smooth step (Fig. 2a) with tabs mounted at the edge of the ledge with height \( \Delta = 6 \) mm and with spacing \( P = 25 \) mm (Fig. 2b) and \( P = 50 \) mm (Fig. 2c). In the first case, a stagnant area is formed behind the step boundary in the central zone; it is also clearly visible with the help of oil-black visualization [3]. In the
thermogram (Fig. 2a) this is the most heated area. The colder zone is in the area of attachment. Tabs on
the ledge boundary (Fig. 2b) change the flow structure in the near zone behind the step. Directly in
the wake behind the tabs the heated area is formed, and between the tabs there is a colder one caused
by the occurrence of longitudinal vortices. The cold region shifts to the ledge, and the area of the
return flow decreases as in [1]. At an increase in spacing between the tabs (fig. 2c, P = 50 mm) their
effect on the separation flow weakens and the size of the recirculation region increases again.

![Figure 2](image)

**Figure 2.** Thermograms of heat exchange surface behind a backward-facing step. (a) Smooth ledge.
(b) Rectangular tabs with a height of 6 mm with spacing $P = 25$ mm. (c) Rectangular tabs
with a height of 6 mm and spacing $P=50$ mm. Flow direction from bottom to top.

As it was shown in [2], the tabs with height $\Delta = 3$ mm, installed on the step boundary, have weak
effect on heat transfer. Thus, for tabs $\Delta / H = 0.3$ and $P / H = 2.5$, the increase in $N_u_{\text{max}}$ is 8% compared to
the case of flow separation behind a smooth step. In this case, $N_u_{\text{max}}$ is localized at 5.26 calibers from
the ledge, while in the case of a smooth step $X_{\text{max}} / H = 6$. A decrease in $X_{\text{max}} / H$ indicates a reduction in
the recirculation region. The authors of [2] found the optimal ratio for tabs ($\Delta / H = 0.3$, $P / H = 2.33$), at
which the length of the recirculation region becomes minimal.

For tabs with a height of $\Delta = 6$ mm, the maximum effect of heat exchange intensification was
achieved when the tabs were located on the edge of the step [2]. Therefore, all experiments on the
influence of the inclination angle of tabs $\alpha$ were carried out for this particular case. The results of
experiments on the effect of the angle of attack are presented in a series of graphs in Fig. 3.

For rectangular tabs, the highest $N_u_{\text{max}}$ value is reached at a step $P / H = 2.5$ (Fig.3a) for the angle
$\alpha = 110^\circ$. Then the Nu value begins to decrease rapidly and at 16 calibers this value practically equals
the data for the ledge without tabs. At this angle, the heat transfer is higher than for $\alpha = 90^\circ$, and this is
apparently due to the fact that the tabs additionally disturb the secondary flow. In the work [1] it was
shown that the influence of tabs mounted on the ledge boundary with a step $P / H = 2.33$ and with a
height $\Delta / H = 0.6$ stops at 4 calibers. At the initial section for rectangular tabs with $P / H = 2.5$, installed
at an angle $\alpha > 90^\circ$, the heat transfer is higher than at $\alpha < 90^\circ$. This is probably due to the fact that at a
blunt angle $\alpha$ there is prevailing tendency of the secondary flow disturbance, and at an acute angle no
additional effect takes place.

Increasing the step between tabs leads to a decrease in the value of $N_u_{\text{max}}$. Except for the angle of
$45^\circ$, where the heat transfer is larger than at an angle of $135^\circ$, this is associated with a decreasing
influence of the tabs on the secondary flow at a blunt angle. Triangular tabs have less influence on
heat transfer in comparison with rectangular ones, since they (in terms of their area) are less immersed
in the boundary layer. Installing the tab at an angle even less immerses it in the boundary layer, and
the influence of tabs on heat transfer is even more reduced. For tabs with $P / H = 25$ at blunt angles $\alpha$ the
heat transfer is higher than at acute angles at the same area of the flow section.
Figure 3. Profiles of transversely averaged Nu number behind the step with tabs of rectangular form: $P = 25\text{ mm}$ (a), $P = 50\text{ mm}$ (b) and triangular form: $P = 25\text{ mm}$ (c), $P = 50\text{ mm}$ (d).

Figure 4. The coordinate of the maximum heat transfer coefficient at different angles of tab installation.
Experimental data on the magnitude of the coordinate of the maximum value of the Nusselt number are presented in Fig. 4. For two-dimensional barriers, the maximum heat transfer coefficient, as well as the coordinate of the flow attachment point [4], is located at the smallest distance from the ledge at \( S/H = 4 \div 6 \), but the maximum heat transfer coefficient is located downstream. In the work [5] it was noted that the most significant deviation occurs in the case of the tab location on the edge of the backward-facing step, when the ratio of the coordinate of the attachment point to that of the maximum of the local heat transfer coefficient reaches \( X_r/X_{\text{max}} = 0.88 \). In this case, the barriers placed in front of the step serve as a source of large-scale turbulent vortices, which is indirectly evidenced by the shape of the profiles of longitudinal velocity pulsations [6]. In contrast to two-dimensional barriers, the tabs placed on the ledge boundary, according to [2] maximally approach the coordinate \( X_{\text{max}} \) to the ledge, since the intensity of the longitudinal vortices behind the tabs is significantly reduced due to the influence of the wall. Rectangular tabs installed with spacing \( P=25 \text{ mm} \) reduce the coordinate \( X_{\text{max}} \) by more than 55\%, and with spacing \( P=50 \text{ mm} \), the minimum value of \( X_{\text{max}} \) is achieved at an angle of 110º. The same trend is observed for triangular tabs, but a decrease in the \( X_{\text{max}} \) value is manifested there to a lesser extent.

**Figure 5.** The maximum value of Nusselt number \( \text{Nu}_{\text{max}} \) at different angles of tabs installation.

It is known that the intensity of large-scale turbulent vortices increases with increasing height of the barrier. In this case, large-scale structures reach the heat exchange surface, thereby providing heat transfer enhancement. Changing the inclination angle of the tab \( \alpha \) leads to a certain reduction of its projection on the vertical axis. For this reason, the maxima of heat transfer, as it is seen in Fig. 5, are grouped in the region of approximately \( \alpha \approx 90^\circ \), when the height of the tab is the largest. At the same time, it should be emphasized that at angles \( \alpha > 90^\circ \), when the tabs are inclined towards the flow, there is an additional flow turbulentization, increasing the intensity of heat exchange. So at the angle \( \alpha = 110^\circ \) the value of \( \text{Nu}_{\text{max}} \) for rectangular tabs with spacing \( P/H = 2.5 \) increases 1.6 times in comparison with the ledge streamlining at the absence of barriers. At their wider spacing \( (P/H = 5) \) this value falls to 1.3, but nevertheless the influence of counter-directed tabs is noticeable. The decrease in heat transfer with a decrease in the number of tabs is obvious, since additional tabs intensify vortex formation. However, it should be taken into account that the hydraulic resistance can increase non-proportionally to the increase in heat transfer. Therefore, the practical use of tabs as a means of heat transfer enhancement is necessary to determine the parameter of thermal-hydraulic efficiency. The
experimental determination of this parameter is an independent problem and is not considered in this paper.

When using triangular tabs, the intensity of the pair of vortices formed in the wake behind them decreases because of the reduction in their surface area, which is the source of vortex formation. This leads to a decrease in the $N_{\text{u}}_{\text{max}}$, as illustrated by Figure 5. The maximum heat transfer values for triangular tabs also fall with increasing step between them. The largest value for $P/H=2.5$ falls on the angle of $90^\circ$, and for $P/H = 50$ on $\alpha =110^\circ$.

**Summary**
The influence of the form and the angle of orientation of tabs on heat transfer in the separation region behind the backward-facing step at the number of $Re = 4000$ has been investigated. The used tabs have rectangular and triangular shapes and the same height of 6 mm. The angle of attack and the step between the tabs vary. The installation of tabs approaches the area of maximum heat transfer to the ledge; at that rectangular tabs are more effective, since the area of the flow perturbation is larger. The smallest and largest angles reduce the maximum heat transfer. The largest heat transfer is observed on the tabs installed either perpendicular to the flow or at angle $110^\circ$.

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