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Experimental investigation of heat-hydraulic characteristics of smooth and dimpled surfaces behind the cylinder

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Abstract. The drag and heat transfer coefficients of smooth and dimpled surfaces located in the wake of a cylinder are experimentally determined. The cylinder, 8 mm in diameter, was placed in a 30 mm-high slot channel. In the experiments the cylinder location along the channel height varied: the gap between the cylinder and the wall under consideration ranged from 0 to 21 mm. The cylinder was unheated. The drag coefficients of the smooth and dimpled surfaces were determined by directly weighing the models on a single-component strain-gauge balance. The local values of the heat transfer coefficients were determined by means of recording the rate of the model surface cooling using an infrared imager. The Reynolds analogy factor for the above-mentioned models ranged from 1.0 to 7.75 depending on the particular surface and the gap between the cylinder and the wall.

1. Introduction

To increase the efficiency of heat transfer systems the heat transfer processes should be intensified. The most widespread means of attaining the desired balance between the heat transfer and the drag is the use of heat transfer intensifiers.

Among the most known methods of intensifying we will consider the superimposition of dimpled surfaces and the insertion of a cylinder transverse to the flow direction. Dimpled surfaces ensuring a moderate (up to a factor of 1.5) increase in the heat transfer accompanied by an equal or lagging increase in the drag. The insertion of a cylinder leads to the breakup of thermal and dynamic boundary layers and is accompanied by heat transfer enhancement and friction drag reduction in the wake of the cylinder. However, an increase in the total drag, which in this case is the sum of the friction drag on the wall and the cylinder form drag, is in most cases considerably greater than an increase in the heat transfer parameters.

The first studies, in which the boundary layer breakup by a cylinder was considered, were devoted to an experimental investigation of flow along a flat plate [1-4]. Later, this question was studied both numerically [5] and experimentally [6]. Flows in a channel with a cylinder were considered in experimental [7, 8] and numerical [9] studies in which the friction drag reduction was observable. In these papers the average values of the friction drag coefficient on a smooth wall behind a cylinder (c_{xsm}) divided by that in the undisturbed flow (c_{x0}) diminished to (c_{xsm}/c_{x0})_{av}=0.28 [1], together with negative local values down to c_{xsm}/c_{x0} =(-2.86) in the return flow region [9]. A considerable heat transfer enhancement was also observable: the average values of the heat transfer coefficient on a smooth wall behind the cylinder (St_{sm}) divided by that in the undisturbed flow (St_0) amounted to

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 $(St_{sm}/St_0)_{av}=1.62$, while the local values amounted to $St_{sm}/St_0=2.69$ [9]. This oppositely directed influence on the heat transfer and the drag friction is called in the literature the dissimilarity of heat and momentum transfer [3, 5, 9, 10].

There has been much research devoted to the heat-hydraulic efficiency of dimpled surfaces [11]. In [12] a channel with angled ribs superimposed on one of the walls and a staggered dimple array between the ribs were experimentally investigated. The highest local heat transfer enhancement amounted to 5.0 on the ribbed smooth surface, 2.77 on the dimpled surface, and 6.72 on the ribbed dimpled surface. The surface-averaged heat transfer enhancement varied in the experiments from 2.2 to 3.2 for the ribbed smooth surface, from 1.6 to 1.8 for the dimpled surface, and from 2.6 to 3.4 for the ribbed dimpled surface.

Apparently, the application of a dimpled relief on a surface embedded in the wake behind a detached cylinder in a transverse flow can increase its heat-hydraulic efficiency.

In this study, the interaction of intensifiers of two types is considered, namely, a cylinder placed in a slot channel (the cylinder location along the channel height varied) and dimples mounted in the cylinder's wake.

2. Experimental setup uncertainties of the measurements

The experimental investigations were performed in a subsonic wind tunnel [13, 14]. Working slot channel was L=1080 mm in length, H=30 mm in height, and B=300 mm in width.

The upper and lower channel walls were made sectional. One of the sections on the lower wall was replaced by a working section intended for determining the heat-hydraulic characteristics of different surfaces (figure 1). In one of the sections of the upper wall a window made of a Zn-Se polycrystal, transparent in the infrared radiation range, was made.

The working region (figure 1) consisted of two floating elements suspended on single-component strain-gage balance (elastic elements). Two models, 125 mm in length and 100 mm in width, were mounted on the floating elements, one of the models being smooth and the other having the relief under study. Above the working section the ThermaCam SC3000 infrared imager was placed for investigating the thermal characteristics of the models. In the process of a comparative experiment the values of the heat transfer enhancement and the drag increase on a dimpled surface, compared with placed in parallel smooth surface, were measured.



Figure 1. Schematics of the working channel.

In investigating the drag coefficients the flow core velocity varied in the range u=10-100 m/s. The heat transfer enhancement was investigated in one regime, in which the flow core velocity was u=100 m/s. The Reynolds number based on the boundary layer length varied in the range Re_x=0.6-4.7 · 10⁶ (in investigating the heat transfer coefficients Re_x=4.8 · 10⁶). The Reynolds number based on the cylinder diameter varied in the range Re_d=5.8 · 53.3 · 10³ (in investigating the heat transfer coefficients Re_d=53.3 · 10³). The Reynolds number based on the channel height varied in the range Re_H=0.2 · 2 · 10⁵ (in investigating the heat transfer coefficients Re_H=2 · 10⁵). In accordance with the recommendations given in [4], the cylinder diameter was taken as the scale length for the flow.

The drag coefficient was determined by means of directly weighing the models on the singlecomponent strain-gage balance [14, 15] with account for variation in the static pressure along the length of the floating elements. The heat transfer coefficient was determined using the time-dependent heat transfer method [14]. The processing method is presented in detail in [13].

The estimate of the uncertainties in measuring the heat-hydraulic characteristics was obtained for the 95% confidence interval, in accordance with the method presented in [16] (see table 1).

Measured quantities						Calculated quantities				
N⁰	Quantity	Measurement range		Ucor	Mo	Quantity	Range of variation		$U_{0,95}$	
		min	max	00,95	JN⊵	Quantity	min	max	min	max
1	T_0	353 K	368 K	0,9 K	1	Re_d	$5.8 \cdot 10^3$	$53.3 \cdot 10^3$	0.4%	5%
2	Т	313 K	368 K	1 K	2	C_{x0}	$3.5 \cdot 10^{-3}$	$4.7 \cdot 10^{-3}$	5%	
3	p^* - p_s	0.25 kPa	6 kPa	26 Pa	3	St_0	1.68.10-3		5.40%	
4	$F_{\Sigma 0}$	0.014 N	0.342N	0.002 N	4	C_{xsm}	-8.18·10 ⁻³		9.3·10 ⁻³	
5	F_{Σ}	0.015 N	1.54 N	0.008 N	5	C_{xd}	$-17.7 \cdot 10^{-3}$	$21.1 \cdot 10^{-3}$	5%	35%
					6	Stsm. Std	$1.26 \cdot 10^{-3}$	$5.61 \cdot 10^{-3}$	3 5%	16%

 Table 1. Uncertainties of the measurements.

3. Geometries under consideration

The experimental investigation was performed in an undeveloped flow in the channel. The trailing edge of the cylinder was at a distance of 700 mm. In the experiments the gap between the lower wall of the channel and the cylinder varied in the range c=0-21 mm (c/d=0-2.625). In investigating the heat transfer coefficients the leading edges of the models were set at distances of 0 (x/d=0) and 40 mm (x/d=5). Thus, the local values of the heat transfer coefficients on the smooth and dimpled surfaces were determined at distances x=0-165 mm from the trailing edge of the cylinder (x/d=0-20.625). The floating element area-averaged values of the drag coefficient were determined in the region x=40-165 mm (x/d=5-20.625). In the experiments, along with the smooth surface model with the staggered array of spherical dimples (print diameter was 7.75 mm and depth was 1 mm) was placed. Longitudinal and transverse pitches of array were $t_x=8$ and $t_y=9$ mm.

4. Results of experimental investigations

In figure 2a we have plotted the values of c_{xsm}/c_{x0} (variation in the smooth model drag in the cylinder's wake c_{xsm} with respect to the same model in the undisturbed flow c_{x0}) as a function of the gap between the wall and the cylinder at Reynolds numbers Re_d=5.3-53.3·10³. As noted above, the values of c_{xsm}/c_{x0} are averaged over the region x/d=5-20.625.

As can be seen in figure 2a, c_{xsm}/c_{x0} is almost independent of Re_d for all cylinder locations. Similarly to [1], the negative values of c_{xsm}/c_{x0} are apparently due to the occurrence of large-size regions of return flow behind the cylinder. As the cylinder recedes from the wall (with increase in *c*) the air starts to flow beneath the cylinder, the return flow becomes less intense, and the values of c_{xsm}/c_{x0} increase. The negative values of the friction drag coefficient in the return flow regions determined by weighing on the floating elements are also in agreement with the results of [17]. In this paper a decrease in the momentum loss thickness was observable behind the cylinder. An increase in c_{xsm}/c_{x0} to the values greater than unity is apparently due to an increase in the flow velocity near the wall and a partial breakup of the boundary layer.

In figure 2b we have plotted the dependence of c_{xd}/c_{xsm} (variation in the dimpled plate drag c_{xd} with respect to that of the parallel smooth plate in the cylinder's wake c_{xsm}) at different Reynolds numbers Re_d. As noted above, the quantities c_{xd}/c_{xsm} are averaged over the x/d=5-20.625 region. For the sake of comparison, in figure 2b the values of the increase in the drag for the dimpled surfaces in the undisturbed flow are also presented for the minimum and maximum Reynolds numbers.

As can be seen in figure 2b, for dimpled surface the ratios c_{xd}/c_{xsm} for the gap c/d=2.625 are only slightly greater than the corresponding values in the undisturbed flow (dotted line). The ratio c_{xd}/c_{xsm} increases with decrease in the gap width c. This is apparently due to the fact that the drag coefficients of the arrangements in the undisturbed flow are related with the characteristic interaction of the vortex

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structures emerging from the dimples located in the neighboring rows [18]. The appearance of largescale vortex structures leads to the violation of this interaction and an increase in the drag.

In figure 3 we have plotted the distributions of the ratio St_{sm}/St_0 (heat transfer enhancement relative to the undisturbed flow) in the x/d=0-20.625 region behind the cylinder for c/d=0-2.625 at the Reynolds number $Re_d=54\cdot10^3$. The values of St_{sm}/St_0 are averaged over the smooth model width.

A considerable nonuniformity of the heat transfer coefficient distributions for all cylinder locations (except from the c/d=2.625 case) should be noted.







Figure 3. Heat transfer enhancement behind the cylinder.

In figures 4 the fields of St_d/St_{sm} (variation in the dimpled plate heat transfer coefficient St_d with respect to that of the parallel smooth plate in the cylinder's wake St_{sm}) on the surface of the dimpled model are presented for and c/d=0.5.

In considering the St_d/St_{sm} distribution in figure 4 an increase in the area inside the dimples occupied by the low, $St_d/St_{sm}<1$, values directly behind the cylinder should be noted. In the immediate proximity of the cylinder maximum and minimum values on the dimples are not clearly expressed and then the St_d/St_{sm} distributions along the plate begin to approach those in the undisturbed flow. With distance from the cylinder the minimum and maximum St_d/St_{sm} values come closer to the corresponding values in the undisturbed flow. As in the case of a smooth wall, maximum values of St_d/St_0 are associated with the c/d=0.5 gap and correspond to the flow reattachment points, near the trailing edges of the dimples. For all cylinder locations the St_d/St_{sm} distributions are similar in nature

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Figure 4. Field of the heat transfer coefficients St_d/St_{sm} for the dimples for c=4 mm.

5. Heat-hydraulic efficiency of the surfaces in the wake of the cylinder

The applicability of any heat transfer intensifiers in the heat-exchange equipment is characterized by their heat-hydraulic efficiency. It is the expression $TP=(St/St_0)/(c_x/c_{x0})^{1/3}=(Nu/Nu_0)/(c_x/c_{x0})^{1/3}$ is often taken as the criterion determining the applicability of intensifiers [19]. However, in the questions devoted to the violation of the similarity of the thermal and dynamic boundary layers it is worthwhile to consider the quantity $St/(c_x/2)$ or the Reynolds analogy factor $RAF=(St/St_0)/(c_x/c_{x0})$.

It is the Reynolds analogy factor that was taken as the heat-hydraulic characteristic of the surfaces considered. It should also be noted that in determining the variations in the drag we used the absolute values of the relative drag coefficient c_x/c_{x0} .

The dependence of RAF on the cylinder location is presented in figure 5a for all the surfaces considered. The maximum RAF values correspond to c/d=0.375 and to minimum values of the drag coefficient. In the figure the averaged data of studies [1, 3] for flow along a plane wall and the data of [9] for a cylinder mounted on a channel wall are presented. Clearly that our data are somewhat lower than those given in [3, 9]. Apparently, this is due to a larger friction drag coefficient on the smooth and dimpled surfaces.

In figure 5b the dependences of $(St_d/St_{sm})/(c_{xd}/c_{xsm})$ are plotted for the dimpled surface. This quantity diminishes with increase in the gap width c/d. This is due to a considerable increase in the relative drag coefficient c_{xd}/c_{xsm} . A decrease in the gap leads to a slight decrease in the relative heat transfer coefficient St_d/St_{sm} .



Figure 5. Reynolds analogy factor for the smooth and dimpled surfaces (a) and the quantity $(St_d/St_{sm})/(c_{xd}/c_{xsm})$ for the dimpled surfaces (b) as functions of the gap between the cylinder and the wall c/d.

6. Summary and conclusions

On the basis of the experimental investigation performed the following conclusions can be made concerning the effect of large-scale disturbances introduced into the flow by a transversely set circular cylinder on the heat-hydraulic characteristics of smooth (the relative drag c_{xsm}/c_{x0} and heat transfer

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 St_{sm}/St_0 coefficients divided by their values on the smooth wall in the undisturbed flow) and dimpled (c_{xd}/c_{x0} and St_d/St_0) surfaces embedded in the cylinder's wake.

The friction and heat transfer coefficients considerably depend on the width of the gap between the surface under study and the cylinder.

There exist certain values of the gaps, at which the coefficients of friction drag (averaged over the surface under study) and heat transfer (both local and average) pass through maxima.

The mean values of the heat transfer coefficients in the cylinder's wake are higher than the values determined on the same surface in the case of the absence of the cylinder. The mean values of the drag coefficient can be both smaller and higher than the values on the smooth surface in the absence of the cylinder.

For all cylinder locations the values of the relative drag coefficients c_{xd}/c_{xsm} of dimpled surface in the cylinder's wake are greater than the corresponding values in the undisturbed flow.

The heat-hydraulic efficiency of the dimpled surface in the cylinder's wake turns out to be lower than the values on the smooth surface for all cylinder locations.

The heat-hydraulic efficiency of the smooth $(St_{sm}/St_0)/(c_{xsm}/c_{x0})$ and dimpled $(St_d/St_0)/(c_{xd}/c_{x0})$ surfaces in the cylinder's wake is higher than the values in the case of the absence of the cylinder and has a clearly expressed maximum at certain gap widths.

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