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Computational and experimental evaluation of heat transfer intensity in channels of complex configuration for gas flow with different levels of turbulence

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Abstract. Disclosure of the physical mechanism of the influence of the turbulence intensity of gas flows on the heat transfer level in pipes of different configurations is an urgent task in the field of heat and power engineering. A brief overview of the literature on this topic is given in the article. A description of the boundary conditions for modeling is presented. The main characteristics of the experimental stand and measuring instruments are described. The purpose of this study is to study the effect of the initial turbulence level of a stationary gas flow on the heat transfer intensity in long pipes with different cross sections. The study is carried out using numerical simulation. The simulation results are qualitatively confirmed using experimental data. The values of the local heat transfer coefficient are shown to increase from 5 to 17% with increasing turbulence intensity (from 2 to 10%) in pipes with different cross sections. The heat transfer intensity in a triangular pipe is found to increase up to 30% compared to a round pipe. It is revealed that there is an up to 15% suppression of heat transfer in a square pipe compared to a round pipe. The data obtained may be useful for the design of flow paths and gas exchange systems for power machines and installations.

1. Introduction

It is known that the heat transfer level in parts, assemblies and systems of various technical devices largely determines their efficiency, reliability and safety [1, 2]. Therefore, the assessment of the heat transfer intensity of flows in gas-dynamic systems of complex configuration at different turbulence levels remains an urgent problem in science and technology.

A brief review of modern research on this topic emphasizes the activity of scientists and specialists in the field of heat transfer control by influencing the gas dynamics of liquid and gas flows. It is possible to single out fundamental studies on the influence of the free-flow turbulence level on the heat transfer rate of a flat plate [3], as well as research on the development of an original method for intensifying heat transfer by changing the gas flow dynamics (increasing the level of turbulence) [4]. The results of such studies can be applied in various fields of science and technology, where it is necessary to control the amount of heat transfer. Analysis of articles by other authors has shown that the influence of the gas-dynamic characteristics of flows (in particular, the turbulence intensity) on the heat transfer level is of great importance in the nuclear industry when cooling nuclear reactors [5, 6]. Heat transfer intensification by controlling the flow gas dynamics is widely used in the field of turbine engineering [7-9]. Gramespacher et al. [7] investigates the effect of surface roughness on the...
turbulence intensity of flows and, accordingly, on the heat transfer level. He et al. [8] propose to improve heat transfer in order to increase the efficiency of cooling of turbine parts and assemblies, based on numerical simulation. The turbulence level of flows is of great importance for the heat exchange intensity in various heat exchangers [10-12]. For example, Gu et al. [10] fine-tunes the design of cooling fins for a heat exchanger taking into account gas-dynamic effects based on experimental studies. Kura et al. [11] improves the efficiency of heat exchangers through the use of turbulent counter jets. It should be noted that there are other technical applications in which the gas-dynamic parameters of flows have a strong influence on the functioning of machines and installations: the flow of nanofluids in heat exchangers [13], the combustion of fuel-air mixtures in combustion chambers [14], and the flow of gases in gas exchange systems of piston engines [15]. In most cases, there is a pattern that an increase in the flow turbulence level causes an intensification of heat transfer. Thus, the main goal of this research is to study the effect of the initial turbulence level of a stationary gas flow on the heat transfer intensity in long pipes with different cross sections based on physical and mathematical modeling and experimental data.

2. Description of the experimental technique and mathematical model

The object of the study was gas dynamics and heat exchange of air flows. The subject of the study was pipes with cross-sections in the form of a circle, square and triangle. In all cases, the length of the pipes was 1 m. The geometric dimensions of pipes with different cross-sections were chosen based on the equality of the areas of flow cross-sections. Accordingly, the inner diameter of a pipe with a circular cross-section was 26 mm, with a square cross-section – 24 mm, and with a triangular cross-section – 34 mm.

A brief description of the mathematical model for modeling stationary gas flows in pipes at different initial levels of turbulence is given below. The modeling is carried out in a three-dimensional formulation of the problem in a modern CFD system based on the finite element method. The LowRe k-ε turbulence model is chosen to simulate the processes in this work. The selection and analysis of turbulence models for predicting the intensity of heat transfer for the boundary conditions characteristic of this study is described in detail in [16]. It is known that the widespread use of the k-ε turbulence model is due to its relative simplicity, stability to inaccuracies in setting the boundary conditions, and sufficient accuracy of the simulation results for many cases [17].

In the case of mathematical modeling, the initial turbulence parameters (turbulence scale 1m) and the average gas flow velocity \( w_{\text{ave}} \) were set as boundary conditions at the flow inlet to the pipes. The average speed varied in the range from 10 to 100 m/s (20,000 < Re < 220,000). The initial turbulence scale 1m varied from 10% to 30%. The working medium in the mathematical model was a real gas (air). The values of the physical properties of the gas flow in the pipes were taken equal to the properties of real air at 40 °C. The pipe walls were set as impermeable with a constant temperature of 120 °C. A volumetric tetrahedral grid with more than 2.5 million computational cells was built as a grid model. Detailed information on the grid model for this study can also be found in [16].

The laboratory bench was created for the experimental study of the heat exchange characteristics of stationary gas flows (Figure 1).

![Figure 1. Diagram of the experimental setup: 1 – the initial section of the pipe; 2 – turbulator; 3 – investigated pipe; 4 – connecting](image-url)
channel; 5 – pump.

The pipes with above described geometrical dimensions were used in the experiments. The working medium was air with a temperature of 20-22 °C. The air in the pipes moved due to vacuum created by the evacuation pump. The average air flow velocity was from 5 to 75 m/s (10,000 < Re < 170,000). A different initial level of flow turbulence was created by stationary turbulators (the turbulence intensity Tu of the flows ranged from 2 to 10%). Static flat-type generators in the form of plates with holes of different diameters (from 2 mm to 8 mm) were used to create different levels of flow turbulence. In this study, the turbulence intensity Tu was defined as the ratio of the rms pulsation velocity component to the average velocity of the investigated flow.

Measurements of the instantaneous values of the air flow velocity and the local heat transfer coefficient in three control sections at distances of 100 mm, 300 mm, and 500 mm from the turbulator were carried out in the course of the experiments (Figure 1). The cross section of the control section for a pipe with a circular cross section is shown in Figure 2.

The hot-wire method was used to determine instantaneous values of the flow velocity \( w_x \) and the local heat transfer coefficient \( \alpha_x \). The heated nichrome thread (sensitive element) of the sensors had a length of 5 mm and a diameter of 5 μm. The filament temperature was about 120 °C. The sensing element of the velocity sensor was located approximately in the center of the pipe when measuring the \( w_x \). The flow velocity was determined on the basis of the degree of cooling of the sensing element of the hot-wire anemometer by the incoming flow and, accordingly, the voltage level, to compensate for this cooling (hot-wire anemometer of constant temperature). The sensing element of the hot-wire anemometer sensor was located on a fluoroplastic substrate on the pipe wall in the case of measuring the \( \alpha_x \), i.e., a so-called thermal sensor was used. This sensor measured the frictional stress on the pipe surface. A transition from local friction stresses to local heat transfer coefficients was possible based on the Reynolds analogy for the simplest cases (stationary flow, long straight pipes). The relative uncertainty in determining the air flow rate was about 5.5%, and that for the local heat transfer coefficient was 10.5%. The methods for determining the \( w_x \) and \( \alpha_x \) are presented in more detail in [18].

3. Description of the main scientific and technical results

In this article, the analysis of experimental data is carried out only for the first control section (100 mm) in pipes of different configurations. Thus, the data presented below refer to the developing gas flow in the pipe. For example, the dependences of the local air flow velocity and local heat transfer in a pipe with a circular cross section at different values of turbulence intensity are shown in Figure 3. It can be seen from Figure 3 that the amplitude of pulsations of the local air flow velocity increases (i.e., the pulsation component of the average flow velocity) with an increase in the turbulence intensity. At the same time, the average values of the heat transfer coefficient and the range of fluctuations of the \( \alpha_x \) also increase (while maintaining virtually the same values of velocity \( w_{ave} \)).

A more detailed analysis of the influence of the level of turbulence of the air flow on the intensity of heat transfer in a long pipe can be done on the basis on Figure 4. This figure shows the results of mathematical modeling and experimental data on heat transfer for flows with different levels of turbulence in a pipe with a circular cross section.
It should be noted that the authors failed to unambiguously establish the identity of the parameters, the turbulence scale $l_m$ (this parameter was specified in the CFD-system) and the turbulence intensity $Tu$ (this indicator was calculated for experimental data). Therefore, in the graphs and in the analysis of scientific results, different concepts were used to characterize the turbulence level of flows.

Figure 3. Experimental dependences of the local air flow velocity and the local heat transfer coefficient in a pipe with a circular cross section for the first control section under different initial conditions: $a$ – $Tu = 2\%$, $w_{ave} = 12.8 \text{ m/s}$; $b$ – $Tu = 10\%$, $w_{ave} = 13.1 \text{ m/s}$.

In mathematical modeling, it was found that the heat transfer intensity slightly increased by 1-4% with an increase in the turbulence scale $l_m$ from 10 to 30% (Figure 4a). The simulation results were qualitatively confirmed using experimental data (Figure 4b). It was revealed that there was an increase in the average values of the local heat transfer coefficient by 5-17% with an increase in the turbulence intensity $Tu$ from 2 to 10%. The obtained results correspond to the data of other authors, which are given in the "Introduction" section and the review article [19]. Other authors also recorded an insignificant effect of the turbulence intensity $Tu$ on the heat transfer coefficient $\alpha_{ave}$ (within 3-15%).

Figure 4. Calculated (a) and experimental (b) dependences of the averaged heat transfer coefficient $\alpha_{ave}$ on the average air flow velocity $w_{ave}$ in a round pipeline under different initial conditions: 1 – $l_m = 10\%$; 2 – $l_m = 20\%$; 3 – $l_m = 30\%$; 4 – $Tu = 2\%$; 5 – $Tu = 5\%$; 6 – $Tu = 10\%$.

Further, the analysis of the influence of the level of flow turbulence on the heat transfer intensity in pipes with different cross-sections was carried out (Figure 5 and Figure 6).

On the basis of mathematical modeling, it was found that the heat transfer intensity in a pipe with a triangular cross-section was on average 3-4% higher than in a basic round pipe (Figure 5). In turn, the use of a pipe with a square cross section, on the contrary, led to the suppression of heat transfer by the
same 3-5\% as compared to the base round pipe (Figure 5). It should be noted that such regularities persisted for all values of the turbulence scale studied in this work.

Experimental data qualitatively confirmed the results of mathematical modeling on the influence of the turbulence level of a stationary gas flow on the heat transfer intensity in pipes with different cross-sectional shapes (Figure 6).

The intensity of heat transfer in a pipe with a triangular cross-section was shown to be 10-30\% higher than in a basic round pipe (Figure 6). At the same time, the greatest difference was observed in the values of the average heat transfer coefficient at the highest values of the turbulence intensity. The opposite physical picture took place for a pipe with a square cross section: the heat transfer intensity decreased in the range of 5-15 \% compared to the base round pipe. At the same time, the differences in the heat transfer intensity in the round and square pipes leveled off with an increase in the intensity of turbulence.

Figure 5. Calculated dependences of the average heat transfer coefficient $\alpha_{ave}$ on the average air flow velocity $w_{ave}$ for pipes with round (1), square (2) and triangular (3) cross-sections at different initial turbulence scales: $a - \eta_{lm} = 10 \%; b - \eta_{lm} = 30 \%$.

Figure 6. Experimental dependences of the averaged heat transfer coefficient $\alpha_{ave}$ on the average air flow velocity $w_{ave}$ for pipes with round (1), square (2) and triangular (3) cross-sections at different values of the initial turbulence intensity: $a - \Theta_{u} = 2 \%; b - \Theta_{u} = 10 \%$.

The effect of the pipe cross section on the heat transfer intensity can be explained by the formation of vortex structures in the corners of such channels [20]. These vortex structures significantly change the gas dynamics of the flow and the conditions for the formation of the boundary layer, and, accordingly, the heat transfer intensity between the flow and the pipe walls [21]. Consequently, further research is needed to study the effect of the flow turbulence level and the cross-section shape of pipes on the heat transfer intensity. In the applied aspect, these data can be useful in the design of gas-air
paths of power machines and installations (piston and rotary engines, gas turbines, compressor equipment, heat exchangers, etc.).

4. Conclusions
The brief conclusions from this study are as follows:

1. A mathematical model has been adjusted and an experimental setup with measuring equipment has been created to assess the effect of the turbulence level of a stationary flow on the heat transfer intensity in pipes with different cross-sections.
2. It is shown that the values of the local heat transfer coefficient increase from 5 to 17% with an increase in the level of flow turbulence (from 2 to 10%) in pipes with different cross sections (quantitative values are given on the basis of experimental data).
3. The heat transfer intensity in a triangular pipe is found to increase up to 30% (experimental data) in comparison with the base round pipe.
4. There is an up to 15% suppression of heat transfer in a square pipe (experimental data) in comparison with a round pipe.
5. The obtained data may be useful for accumulating a knowledge base on the influence of the turbulence level of stationary flows on heat transfer in pipes with different cross-sectional shapes. In addition, these data can be used in the design of flow paths and gas exchange systems for power machines and installations (in particular, heat engines).
6. Further research directions are to obtain data on the heat transfer characteristics of stationary flows along the entire length of the pipes, as well as to compare the heat transfer rates for stationary and pulsating gas flows at different turbulence levels.

References
[1] Bacon D H 1989 Basic Heat Transfer (UK: Butterworth-Heinemann) p 182
[2] Dyban, E. P., Epik E Y 1985 Heat Mass Transfer and Hydrodynamics of Turbulized Flows (Kyiv: Naukova Dumka) p 296 (In Russian)
[3] Yang Y, Ting D S-K, Ray S 2021 Thermal Science and Engineering Progress 231 100921
[4] Choi S M, Kwon H G, Bang M, Moon H K, Cho H H 2021 Int. J. Heat and Mass Transfer 173 121242
[5] Abe S, Okagaki Y, Satou A, Sibamoto Y 2021 Annals of Nuclear Energy 159 108321
[6] Qi P, Hao S, Su J, Qiu F, Tan S 2021 Atomic Energy Science and Technology 55(1) 142-150
[7] Gramespacher C, Albiez H, Stripf M, Bauer H-J 2021 J. Turbomachinery 143(8) 081001
[8] He W, Deng Q, Yang G, Feng Z 2021 J. Turbomachinery 143(9) 091005
[9] Bacci T, Picchi A, Lenzi T, Facchini B, Innocenti L 2021 J. Turbomachinery 143(4) 041006
[10] Gu J, Li Z, Wang Q, Lyu J, Wu Y 2021 Applied Thermal Engineering 187 116566
[11] Kura T, Wajs J, Fornalik-Wajs E, Kenjeres S, Gurgul S 2021 Energies 14(11) 105
[12] Alzahrani S, Islam M S, Saha S C 2021 Applied Thermal Engineering 186 116533
[13] Tschisgle S, Kempe T 2021 Int. J. Heat and Mass Transfer 175 121392
[14] Barcelos B D R, Centeno F R 2021 Thermal Science 25(1) 209-220
[15] Plotnikov L V, Zhilkin B P 2021 J. Engineering Physics and Thermophysics 94(3) 687-694
[16] Plotnikov L, Nevolin A, Nikolaev D 2017 EPJ Web of Conf. 159 00035
[17] Launder B E, Spalding D B 1974 Comp. Methods in Applied Mechanics and Engineering 3(2) 269-289
[18] Plotnikov L V 2021 Int. J. Engine Research (Article in press) doi: 10.1177/1468087420987360
[19] Terekhov V I 2021 Energies 14 1005
[20] Kutateladze S S 1990 Heat transfer and flow resistance: A Reference Guide (Moscow: Jenergoatomizdat) p 367 (In Russian)
[21] Brodov Y M, Zhilkin B P, Plotnikov L V 2018 Technical Physics 63(3) 319-324