# Experimental research of turbulent flow frequency spectra

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***Abstract:*** *Hydraulic and heat transfer processes play a very important role in the design and prototyping of aerospace technology. In most cases this technique works under non-isothermal conditions. Non-isothermal conditions may significantly affect heat transfer and hydrodynamic process. Fundamental research of Non-isothermal turbulent flow is required for further engineering modeling. Models for unsteady processes calculation must be based on fundamental turbulent structure research. Moscow Aviation Institute National Research University (MAI) has been building non-isothermal turbulent flow structures since 1989. An experimental facility was designed to provide gas flow heating. Experimental data of a turbulent gas flow structure in isothermal and non-isothermal conditions are presented. The frequency spectra of axial and radial velocity pulsations are based on experimental data received. The results of experimental turbulent flow research demonstrate fundamental non-isothermal processes influence on the flow structure. The main results of non-isothermal experimental research show that there are three specific zones in turbulent flow structure: wall area, maximal turbulent structure transformation and flow core. The analysis of non-isothermal conditions influence on turbulent pulsations generation and development mechanisms is presented. The results show significant distinction in turbulent flow spectra between isothermal and non-isothermal conditions. The present paper describes a method of experimental research, methodology of data processing and non-isothermal turbulent flow spectra results.*

***Key Words:*** *turbulent flow structure, non-isothermal flow, frequency pulsations spectra*

## 1. INTRODUCTION

Non-isothermal processes are typical in all modern engineering systems. For thermal and hydrodynamic processes modeling is necessary to understand the mechanisms of generation, development and dissipation of turbulent vortexes.

Obviously, any thermodynamic influence on turbulent is a matter of importance for turbulent structure.

Only integral combination of fundamental and empirical research is the most effective way for non-isothermal process precise model creation, and as a consequence, for precise engineering calculations.

References to the studies of unsteady conditions influence on the turbulent flows structure and on the thermodynamic parameters can be found in the research works of the 70s of the twentieth century [1-3]. Results of experimental research conducted in Moscow Aviation

Institute hold a significant place among these results. In the mid of 90s, a scientific school of turbulent flows structure was founded in Moscow Aviation Institute by Professor Heinrich Dreitzer.

Turbulent flow structure research carried out in Moscow Aviation Institute has shown a significant impact of changes in flow, or in other words, non-isothermal conditions on the flow structure.

Behavior of turbulent pulsation frequency spectra under isothermal and non-isothermal conditions play a very important role for further analysis.

The authors have previously encountered the need to study the frequency characteristics of turbulent flows [4-8].

Their research of turbulent flows frequency spectra showed that a certain vortex plays significant role in the energy transfer in flow. It means these vortexes transfer the biggest part of energy.

The authors [4-8] identify that such vortexes have the biggest scale and, the lowest frequencies in the range of 50 ... 200 Hz, respectively.

Dyban E. and Epik E. [9] found that in turbulent flows, turbulence generation occurs near the wall and pulsations fade away from the wall to the main flow at all frequencies range. However, the rate of their attenuation at different frequencies differs significantly. The high and low frequency pulsations decrease most quickly, and medium frequency pulsations decrease slower.

Epik E. Ya. and Pioro M. L. [10] researched the unsteady flow on a flat plate. They found that low-frequency vortexes of the spectrum play a significant role in energy transfer. Recent studies described in [11], have a noticeable effect of heating or cooling the wall on the production of turbulence.

However, there is no experimental data of frequency spectra distribution over the channel cross-section, and especially on the non-isothermal conditions influence on the frequency spectra. The experimental research of frequency spectra distribution over the channel cross-section started in MAI in 1998 [12, 13].

C. B. Lee and J. Z. Wu [14] analyzed transition flows in the near wall area and identified with hot-wire pulsations at frequency 2-20 Hz. This spectrum datum is reliable for transition flows. But for fully developed turbulent flow the spectrum can be different from the transition mode. Marek Jaszczur [15] researched turbulent non-isothermal fully developed channel flow using the large eddy simulations.

The model channel has a flat form heated from both sides. In their most recent work Lei Wang, Jian Liu, Safeer Hussain and Bengt Sundén [16] performed large eddy simulations to study the influence of variable viscosity and thermal conductivity on forced convection in a non-isothermal channel flow. The channel has a flat form with cold and warm opposite walls. The results concerning the process of turbulence structure at heated wall is of great interest for the actual research.

## 2. EXPERIMENTAL RESEARCH OF THE TURBULENT PULSATIONS SPECTRA AT ISOTHERMAL AND NON-ISOTHERMAL CONDITIONS

### 2.1 Research methodology and experimental installation

The experimental equipment in Moscow Aviation Institute is based on a hot-wire anemometer system and is able to measure an instantaneous axial and radial velocity and temperature of the gas flow. These measurements can be done with frequency up to 1 kHz. The Reynolds numbers in experiments ranges between 3000 and 30000. The scheme of experimental equipment is presented in fig. 1.

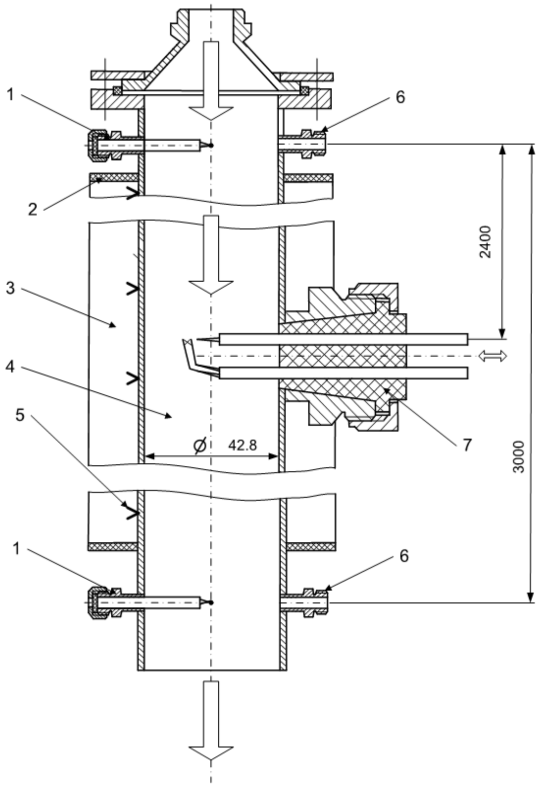


Fig. 1 Experimental installation diagram. 1 – thermocouple fitting, 2 – thermal insulation, 3 – casing-screen, 4 – experimental channel, 5 – pressure gage fitting, 6 – hot-wire anemometer sensors assy.

The non-isothermal conditions are provided by electrical heating of channel's wall. The range of temperature criteria $T_w/T_f$ was from 1.0 up to 1.18. $T_w$ – wall temperature, K. $T_f$ – flow temperature, K.

Detailed description of experimental equipment and research methodology were presented above [17]. The experimental equipment, the data collection, the processing system and experimental methodology allow recording turbulent parameters with a frequency of 2.5 kHz. This measurement frequency allows to identify the turbulent pulsations in all frequency spectra.

For a turbulent flow structure, the frequency analysis method was used, based on turbulent flow spectra concept.

If n is a frequency of pulsations and *F(n)dn* is the percentage of average square-law value of velocity pulsations in the range of frequencies from *n* up to *n+dn*, function *F(n)* represents spectral distribution of average square-law pulsations. Then, according to definition,

$$\int_0^{\infty} F(n)dn = 1 \tag{1}$$

Mathematical, the spectral function *F(n)* is a result of Fourie's transformation of auto-correlation function. Based on turbulent flow structure data, the amplitudes of vortexes pulsations $\rho U_x$, $\rho U_r$ were calculated.

### 2.2 Frequency analysis of turbulent flows in isothermal steady conditions

The preliminary analysis of the frequency spectrum shows that the highest frequencies do not exceed 500 Hz. So, the whole frequencies spectrum was divided into three bands: 30, ..., 70 Hz, 70, ..., 200 Hz and 200, …, 500 Hz. The distribution of axial pulsations' frequency spectra over the channel radius are presented in Fig. 1-3. Each graph corresponds to specific Re numbers. All three graphs for the numbers Re=18700 (Fig. 2), Re=12500 (Fig. 3), and Re=6200 (Fig. 4) look similar, but differ in values. *y/R* – dimensionless distance from the wall.

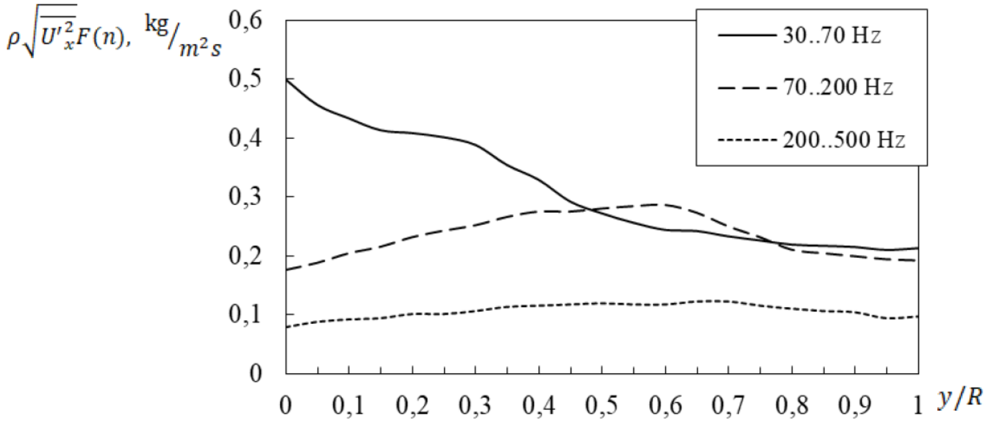


Fig. 2 Axial pulsation amplitudes over the radius in steady isothermal conditions, Re=18700, $T_w/T_f$ =1.

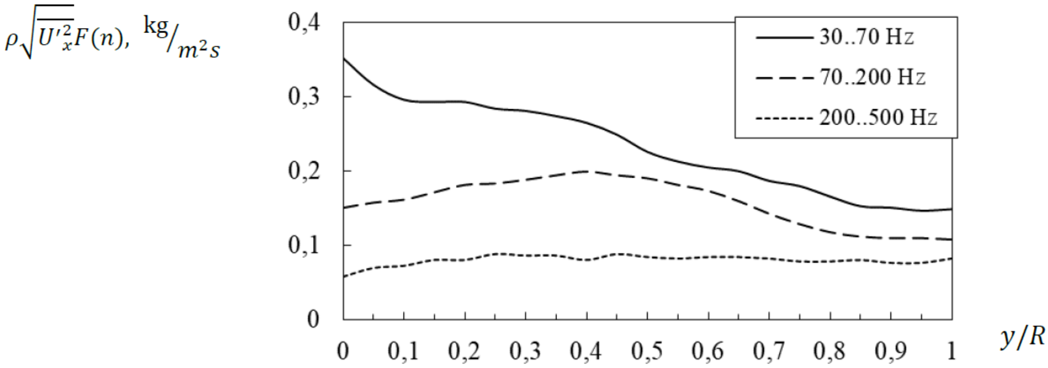


Fig. 3 Axial pulsation amplitudes over the radius in steady isothermal conditions, Re=12500, $T_w/T_f$ =1.

At Re=18700, the amplitude of the frequency range is 30, ..., 70 Hz ("low frequency") near the channel wall is 0.5 kg/m$^2$s and decreases to 0.2 kg/m$^2$s on the channel axis. The amplitude of frequencies 70, ..., 200 Hz ("medium frequency") at the channel wall is approximately 0.2 kg/m$^2$s, gradually growing up to 0.3 kg/m$^2$s at distance from the wall *y/R*=0.5, ..., 0.6 and then reduced to 0.2 kg/m$^2$s on the channel axis.

Frequency range 200, ..., 500 Hz ("high frequency") over the entire radius does not exceed 0.1 kg/m$^2$s. At Re=12500, the amplitude of the "low" frequency's pulsations of the range at the wall is 0.35 kg/m$^2$s and also decreases to 0.15 kg/m$^2$s on the axis. The trend of axial frequencies pulsations remains the same, as at Re=18700.

The amplitude of the "medium" frequencies pulsations at the channel wall is approximately 0.15 kg/m$^2$s, smoothly increasing to 0.2 kg/m$^2$s at *y/R*=0.4, ..., 0.5 and then decreases to 0.12 kg/m$^2$s in the core flow. "High" frequencies pulsations across the entire cross section also do not exceed 0.1 /m$^2$s.

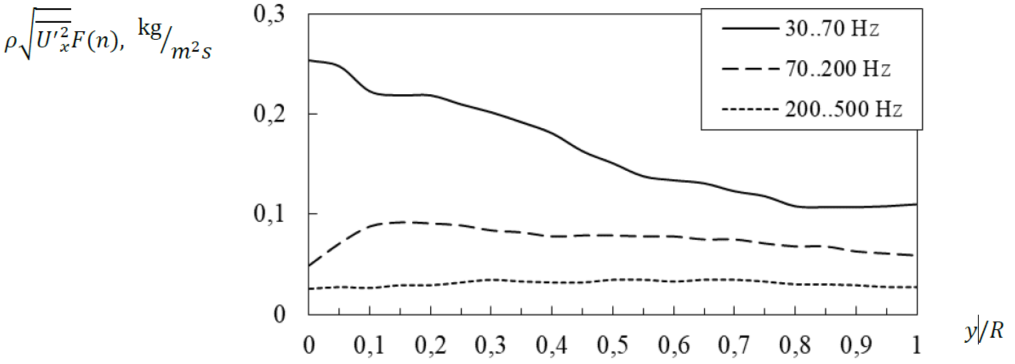


Fig. 4 Axial pulsation amplitudes over the radius in steady isothermal conditions, Re=6200, $T_w/T_f$ =1

The similar axial pulsation amplitudes configuration was found at Re=6200 also, but at lower amplitudes. The amplitude of the "low" frequencies at the wall is 0.25 kg/m$^2$s and decreases to 0.1 kg/m$^2$s on the axis. The amplitude of the "medium" frequencies at the channel wall is approximately 0.05 kg/m$^2$s, and is 0.1 kg/m$^2$s at *y/R*=0.1, ..., 0.3 and then gradually decreases to 0.08 kg/m$^2$s on the channel axis. The amplitude of the "high" frequencies across the entire cross section does not exceed 0.03 /m$^2$s.

The distribution of amplitudes of radial pulsation frequencies over the channel radius is presented in Fig. 4-6. The graphs in Fig. 5-7 demonstrate the similar distribution of the amplitudes of the axial and radial pulsation frequencies. The difference is that the radial pulsation amplitudes are approximately 30, ..., 40% below the axial ones.

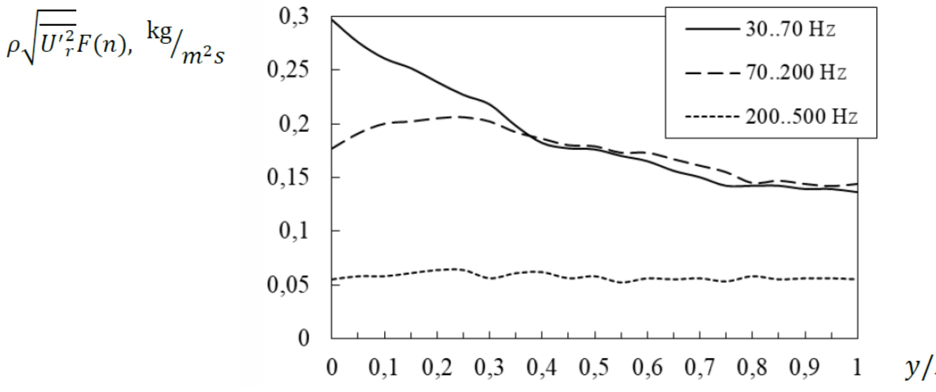


Fig. 5 Radial pulsation amplitudes over the radius in steady isothermal conditions, Re=18700, $T_w/T_f$ =1

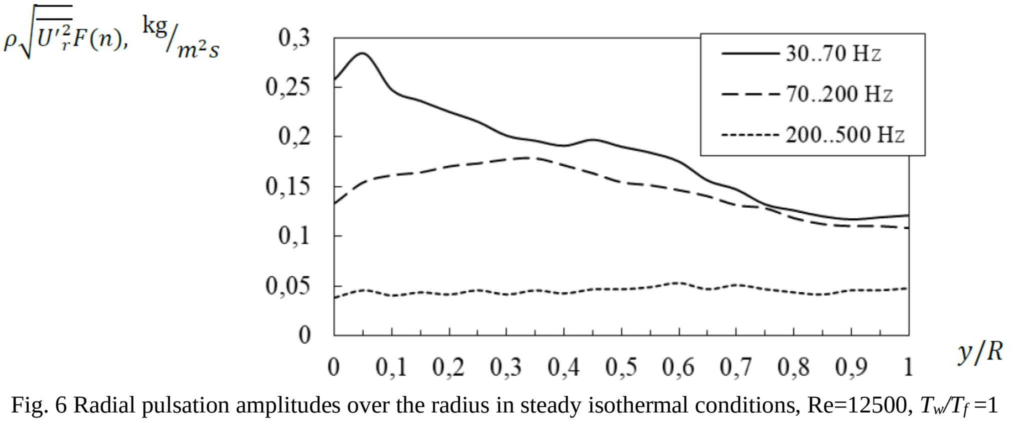


Fig. 6 Radial pulsation amplitudes over the radius in steady isothermal conditions, Re=12500, $T_w/T_f$ =1

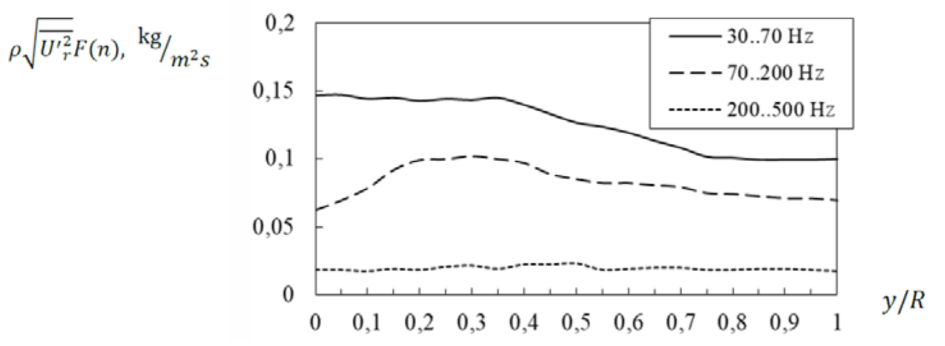


Fig. 7 Radial pulsation amplitudes over the radius in steady isothermal conditions, Re=6200, $T_w/T_f$ =1.

We assume that high ("low frequency") vortex generation occurs at the channel wall. Then the vortexes move from the wall to the channel, and they disintegrate decay into "medium frequency" vortexes. This assumption is quite consistent with many hypotheses and theories of turbulence. "Medium frequency" vortices also appear near the wall. And number of them, i.e. their amplitude, increases when they move to the channel axis due to the "low-frequency" vortices disintegration into "medium frequency" ones. Fig. 2-7 show the Reynolds number Re increases by three times, there is an increase in the pulsations amplitudes, and therefore, in the turbulence generation, by about two times. It should also be noted that amplitudes of the axial pulsations exceed the radial ones by about 1.5 times.

### 2.3 Frequency analysis of turbulent flows in non-isothermal steady conditions

The next step of experimental research was a detection of non-isothermal conditions influence on turbulent flow structure. The experimental data are presented for various temperature coefficient $T_w/T_f$=1,…,1.18 and constant Reynolds criteria. This approach allows to understand the dependence between the non-isothermal impact and the frequency spectra modification.

Figures 8-10 show the distribution of the frequency amplitudes of axial pulsations over the channel cross-section for Reynolds numbers Re=9300 and various non-isothermal criteria $T_w/T_f$=1.18, $T_w/T_f$=1.12 and the isothermal case ($T_w/T_f$=1). In case of $T_w/T_f$=1.18 (fig. 8) the amplitude of the pulsation frequency in range 30, ..., 70 Hz ("low frequency") at the channel's wall is 0.4 kg/m$^2$s and decreases to 0.3 kg/m$^2$s on the axis of channel. The amplitude of frequencies 70, ..., 200 Hz ("medium frequency") at the channel wall is approximately 0.2 kg/m$^2$s, gradually growing up to 0.3 kg/m$^2$s at $y/R$=0.2, …, 0.4 and then stays at 0.2 kg/m$^2$s. The frequency range pulsations 200, …, 500 Hz ("high frequency") over the entire radius slightly exceed 0.1 kg/m$^2$s in the $y/R$=0.3, ..., 0.6.

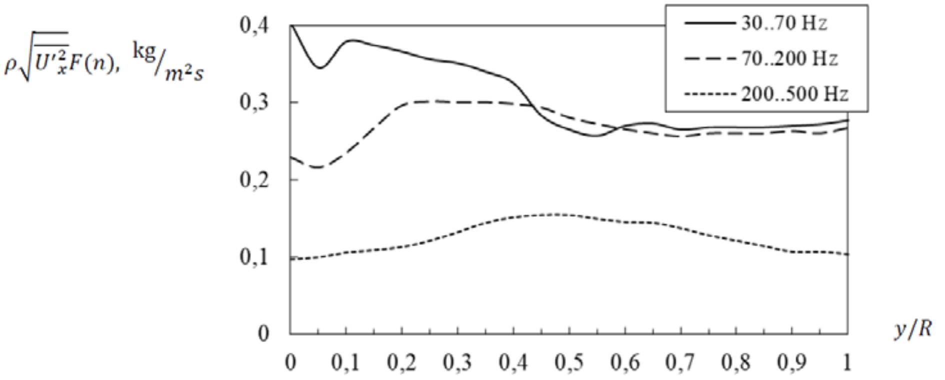


Fig. 8 Axial pulsation amplitudes over the radius in steady non-isothermal conditions, Re=9300, $T_w/T_f$ =1.18.

In case of temperature criteria $T_w/T_f$=1.12 (fig. 9), the axial pulsations amplitude of the low frequency range (30, ..., 70 Hz) at the wall is about 0.25 kg/m$^2$s and gradually decreases to 0.2 kg/m$^2$s on the axis.

The amplitude of the medium frequencies at the channel wall is equal to approximately 0.15 kg/m$^2$s, gradually increasing up to 0.2 kg/m$^2$s at $y/R$=0.3, ..., 0.5 and then decreases to 0.12 kg/m$^2$s on the channel's axis. High frequencies across the entire cross section also do not exceed 0.06 kg/m$^2$s.

Isothermal case at the same Reynolds number is presented in fig. 10. The axial pulsations amplitude of the low frequencies is equal to 0.18 kg/m$^2$s at the wall and decreases to 0.1 kg/m$^2$s on the channel's axis.

The medium frequencies pulsations have an amplitude ca two times less at the channel wall - 0.08 kg/m$^2$s. In an area $y/R$=0.1, ..., 0.2 their amplitude slightly increases up to 0.1 kg/m$^2$s and then gradually decreases to 0.05 kg/m$^2$s on the channel's axis. The amplitude of the high frequencies' pulsations across the entire cross section is insignificant and consists in about 0.03 kg/m$^2$s.

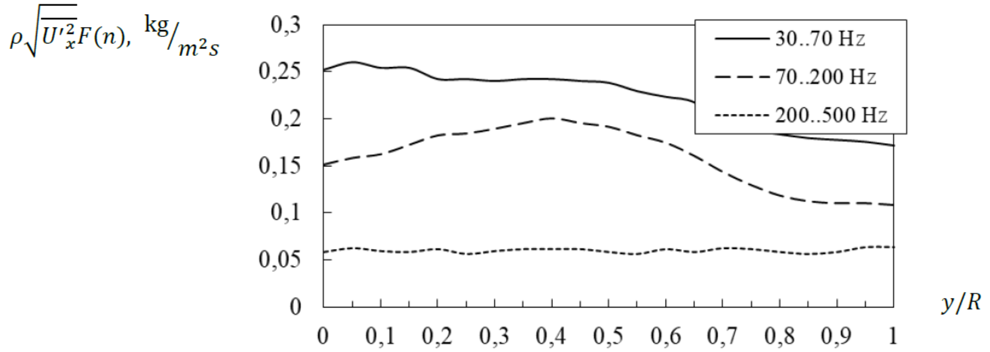


Fig. 9 Axial pulsation amplitudes over the radius in steady non-isothermal conditions, Re=9300, $T_w/T_f$ =1.12.

The distribution of the radial pulsation amplitudes frequencies is presented in figures 11-13. These figures demonstrate a quality similar picture as for axial pulsations.

According to experimental data at non-isothermal conditions by channel wall heating, there is a significant up to three times increase of the amplitude of pulsations in low frequency spectra. Such strong influence was identified at temperature criteria $T_w/T_f$=1.18. Apparently, this effect is due to the more intense pulsation generation.

The growth of the amplitude of pulsations in medium frequency spectra reaches also three times. Before we supposed that low frequency pulsations characterize the big scale vortexes, and high frequency pulsations characterize the low scale vortexes, respectively.

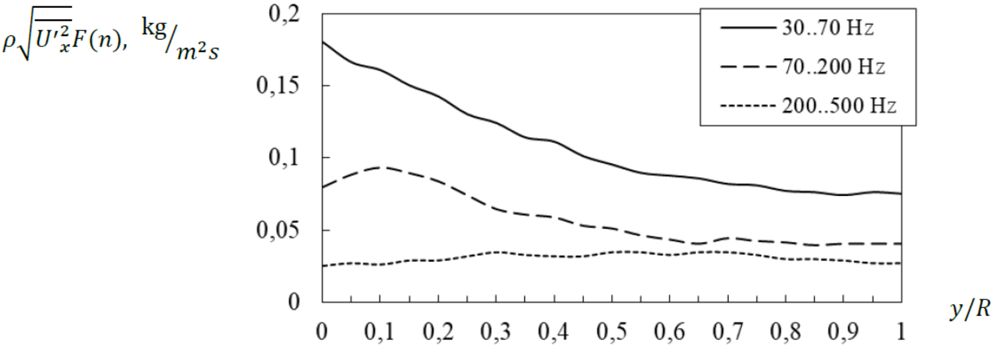


Fig. 10 Axial pulsation amplitudes over the radius in steady isothermal conditions, Re=9300 $T_w/T_f$ =1.

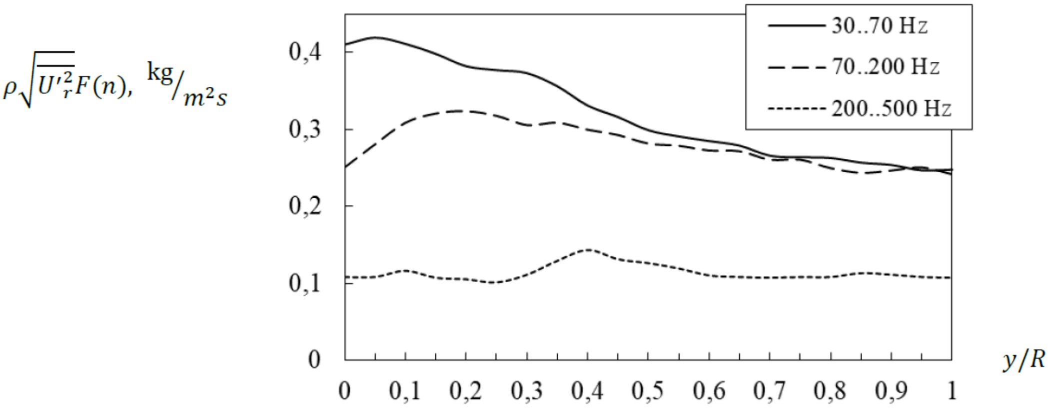


Fig. 11 Radial pulsation amplitudes over the radius in steady non-isothermal conditions, Re=9300 $T_w/T_f$ =1.18.

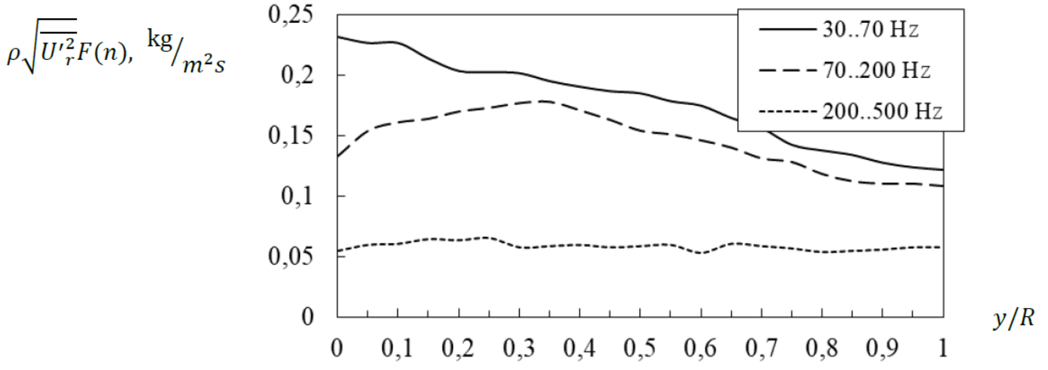


Fig. 12 Radial pulsation amplitudes over the radius in steady non-isothermal conditions, Re=9300 $T_w/T_f$ =1.12.

Against this background, we can note a faster disintegration of large-scale vortices in medium-scale ones during their movement on the channel axis.

Based on that, the following conclusions can be done: heating of the channel wall significantly intensifies the turbulent vortices generation in the entire observed spectrum (30, ..., 500 Hz).

The disintegration of large (“low frequency” – 30, ..., 70 Hz) vortices in high non-isothermal conditions ($T_w/T_f$=1.18) occurs faster than in the isothermal case.

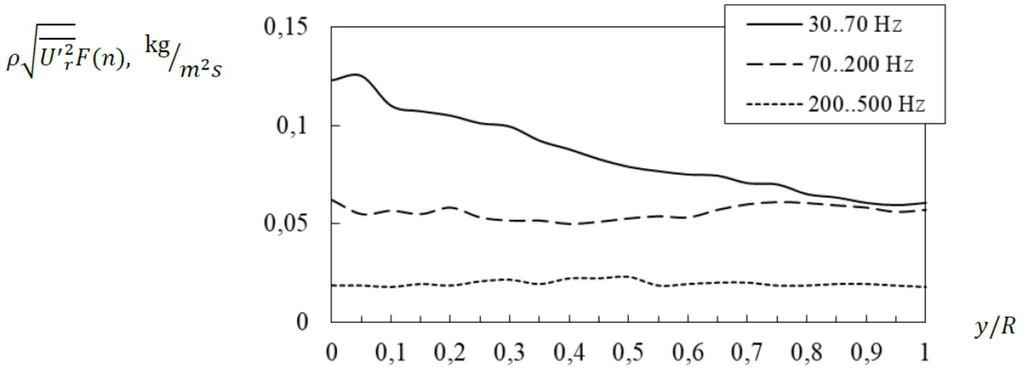


Fig. 13 Radial pulsation amplitudes over the radius in steady isothermal conditions, Re=9300 $T_w/T_f$ =1

# 3. EXPERIMENTAL DATA ANALYZES AND PROPOSAL

## 3.1 Frequency analysis of turbulent flows in non-isothermal steady conditions

Experimental researches of the gas flows frequency spectrum in steady isothermal and non-isothermal conditions come to some proposals concerning the physical processes of turbulence.

So, in conditions of steady isothermal flow on the channel wall the generation of large scale and high energy vortexes (with a pulsation frequency of 30, ..., 70 Hz) and medium scale vortexes (with a ripple frequency of 70, ..., 200 Hz) takes place.

According to amplitude pulsation data, large vortices quantity is more than medium vortexes. By low Reynolds number large vortices generation considerably prevails over medium and small vortexes generation. By higher Reynolds such difference became less. Further, as the turbulent vortexes move from the channel wall to the axis. During this movement large vortices pulsations amplitude decreases and medium vortices pulsations amplitude increases. This fact can be explained as large vortexes disintegrate into smaller ones. With the growth of Reynolds numbers, this process of vortexes disintegration became faster. For example, at $Re$=6200, disintegration zone located in the range of $y/R$=0.05, ..., 0.7, and for $Re$=18700 – in an area $y/R$=0.05, ..., 0.4. At the same time there was no noticeable change in small vortexes with pulsation frequencies 200, ..., 500 Hz, which are generally much weaker than the high energy vortexes of frequency 30, …, 70 Hz along the entire channel cross-section.

Comparing graphs for axial and radial pulsations were also done. This comparison shows the axial pulsations amplitudes are 1.5, ..., 2 times higher than radial ones. Such fact comes to hypothesis of “asymmetry” of turbulent vortices.

The non-isothermal conditions at wall heating up to $T_w/T_f$=1, ..., 1.18 comes to significant (up to three times) increase of large and medium vortices pulsation amplitudes. In other words, there is a faster turbulent vortices generation on the wall.

The zone of vortexes transformation, collapsing of large vortexes into medium ones, definitely became narrower ($y/R$=0.05, ..., 0.35). In the isothermal conditions the zone of vortexes transformation located at $y/R$=0.05, ..., 0.7. This fact comes to the conclusion that the dissipation of vortexes goes much faster. With higher heating ($T_w/T_f$=1.18), the growth of radial pulsations amplitude overtakes the growth of axial pulsations amplitude. So, the difference in their amplitudes became less significant. According to our hypothesis above, the heating of the channel wall makes the vortices “symmetrical”.

When considering the effect of non-isothermal conditions on hydrodynamics, it is necessary to research also the hydrodynamic unsteadiness influence on frequency spectra. It is necessary to independently analyze such effect and combined with non-isothermal conditions. Probably, simultaneous imposition of hydrodynamic unsteadiness and non-isothermal conditions can lead to results other than a simple summation of the effects.

## 3.2 Proposal of physical model of turbulent flow structure changes in non-isothermal steady conditions

Analyzes of experimental data turbulent flows structure [3, 13] and pulsation’s frequency spectra in isothermal and non-isothermal conditions allow to propose a physical model of turbulent flow structure changes in non-isothermal steady conditions. This model is mainly concerned with the physical process in turbulent structure in near wall area.

In previous work [3] turbulent flow in a cross-section was segmented into several zones: zone of viscous sublayer $0 \le \eta \le 5$, zone of vortex structures generation $5 < \eta \le 15$, zone of vortexes structures interaction $15<\eta\leq30$ and area $\eta<30$. Where $\eta$ - dimensionless distance from a wall:

$$\eta = Uy/\nu, \tag{2}$$

where $U$ – average axial velocity, m/s; $y$ – distance from a wall, m; $\nu$ – kinematic viscosity, $m^2/s$.

So, in isothermal conditions in a viscous sublayer $0\leq\eta\leq5$, the flow is not laminar. This zone is periodically under the influence of pulsations coming from zone $5\leq\eta\leq15$. These pulsations represent large volumes of medium with negligible oscillation amplitudes [3]. The interaction of these pulsations viscous sublayer comes to the generation in an area $5\leq\eta\leq15$ vortex structures. New vortices move to the next area $15\leq\eta\leq30$, where there is an active vortexes structures interaction with the main flow. And outside area $\eta=70$ such vortex structures no longer exist. This thesis is also confirmed by recent research [13, 14]. In the near-wall area, the emission and movement of the vortex structure causes a local flow deceleration with a thickness of $\eta\geq30$ and a slight velocity gradient. At the same time, the main stream has enough large mass and speed comparable to an average speed of layer currents. The interaction of these two structures – areas of slow flow and the main flow comes to intense ejection of vortices that form the basis of turbulent fluctuations [3]

In non-isothermal by wall heating conditions ($T_w/T_f>1$), the certain volume of gas in an area at the wall $5\leq\eta\leq15$ can be significantly heated up. The heating of gas comes immediately to its expansion. Expanded gas has a bigger surface for further interaction with large volumes of relatively cold gas. This process in turn leads to more intense vortex emission. Therefore, the turbulence generation is intensified. Intensive generation of turbulent vortexes comes to a faster disintegration during their moving from the wall to the main stream and during their interaction with the relative cold flow.

The authors [13, 14] demonstrate results where mean velocity profile was deformed under non-isothermal conditions in an area $5\leq\eta\leq50$. At the same area the pulsations correlations were higher isothermal conditions 20-100% and the greatest difference was identified very close to the wall. These calculated results [13, 14] are in agreement with the presented experimental data.

This research based on experimental data could be useful for theoretical investigations and mathematical modelling of turbulent flows. In further researches a frequency analysis of turbulent flows in unsteady conditions by flow acceleration and deceleration will be performed.

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