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M3f: Dejan Cvetinović, Rastko Jovanović, Jiří Vejražka, Jaroslav Tihon, Kazuyoshi Nakabe, Kazuya Tatsumi,

MATHEMATICAL MODELLING OF VORTEX STRUCTURES OF THE TURBULENT AXISYMMETRIC AIR JET MODIFIED BY LOW-AMPLITUDE OSCILLATIONS

Roll-up of the vortex structures can be controlled by adding small amplitude modulation of the nozzle exit velocity by an external source of low-amplitude oscillations or self-sustained oscillations generated in the operation of the specially designed whistler nozzles. The aim of experimental investigations, mathematical modeling and numerical simulations provided during project evaluation is to widely investigate properties and the vortex structures of acoustically modified and not modified jet and to find an efficient way of to control them because they are assumed to have great importance in the heat transfer process.

In the paper are presented results of mathematical modeling and numerical simulation of free and impinging turbulent axisymmetric air jet, not modified and modified by low-amplitude oscillations. Results of mathematical modeling showed good agreement with experimental results that demonstrated the ability to control vortex structures in the jet by sound modulations of the nozzle exit velocity. This study can serve as a base for the development and optimization of the technological processes that involve air jet.

M3g: Suzana Lj. Linić, Bojana M. Radojković, Marko D. Ristić, Ivana V. Vasović,

ONE METHOD FOR ORDERING TURBULENCE MEASURING PLACES APPLIED TO FREE-CONVECTION FLOW AROUND THERMAL PLANT COAL MILL

The investigations of the turbulence in the flow are one of the most expensive, thus the improvement of existing ones and the research related to the new methods are in continual development. The multidisciplinary approach led to the application of the infrared thermography in the turbulent boundary layer observations with the endpoint goal of energy and cost savings in its early stages. This work presents the use of the industrial type infrared thermography for identification of the turbulent zones in the free convective flow, so far the less investigated problem related to convection heat transfer. It was shown that the transient spot temperature difference, measured on the complex geometry of the real-scale coal ventilation mill, of the Thermal plant “Kostolac B”, by an infrared camera, is a good parameter for identification of the most influenced positions by turbulence. The defined fields with maximal transient temperature difference are in accordance with theory and values calculated by numerical simulations for clean geometry, confirming the assumptions. The described method is also convenient for use in cases when the other methods are not applicable because of the complex geometry, unapproachable, or for the other similar reasons. The results from this work would support the more precise measurements with the research type infrared camera, the other methods for measurements.

M3h: Mohammad Sakib Hasan, Jelena Svorcan, Aleksandar Simonović, David Daou, Bojan Perić,

CFD ANALYSIS OF A HIGH ALTITUDE LONG ENDURANCE UAV WING

The aerodynamic performance of an airfoil provides specific information on wing design of HALE UAV and is considered as eminent for enhancing its flight conditions. In this paper, numerical investigation of a wing is conducted to predict its preliminary aerodynamic quality. A concise comparison of lift and drag curve obtained from numerical analysis conducted in two different programs, will be the scope of this research. Preliminary aerodynamic performance study including 12 different wings were previously performed in Fortran program 'GLAUERT-trapezoidal wing. From those 12 wings, one wing was selected which has the best aerodynamic performance at an operational altitude of 15000 m. Computational fluid dynamic (CFD) software package, ANSYS Fluent is used for numerical analysis of the selected wing. Two different turbulence models were simulated in this work. Lift and drag coefficients were calculated respectively by varying angle of attacks. Hence, the resulted lift and drag curve generated in GLAUERT were compared with those obtained from ANSYS FLUENT. Additionally, other parameters like flow separation, pressure and velocity contours obtained by different turbulent models were also discussed.

M3i: Bojan Perić, Aleksandar Simonović, Aleksandar Kovačević, Dragoljub Tanović, Miloš Vorkapić,

NUMERICAL ANALYSIS OF AERODYNAMIC PERFORMANCE OF OFFSHORE WIND TURBINE

The increasing size of wind turbine blades leads to various flow phenomena which are influenced by aerodynamic design of blade. Detailed information of flow separation and wake development are important for wind turbine blade designers to optimize blade design. In order to obtain detailed information on the flow field, CFD (computational fluid dynamics) modeling is the topic in many research studies.

In this paper aerodynamic analysis of the reference DTU 10 MW HAWT rotor using finite volume method was done. Numerical simulations are realized in a commercial software package ANSYS FLUENT. Flow field is modeled by Reynolds Averaged Navier-Stokes (RANS) equations using transition SST viscous model. The pressure-based SIMPLEC pressure-velocity coupling and 2nd order spatial discretization schemes were used for calculation. Obtained numerical results for mechanical power, power coefficient, thrust, thrust coefficient, pressure coefficient and relative velocity contours at rated wind speed were considered. The results were compared with the reference results and conclusions were derived.

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ONE METHOD FOR DETERMINING TURBULENCE MEASURING PLACES APPLIED TO FREE-CONVECTION FLOW AROUND THERMAL PLANT COAL MILL

Suzana Lj. Linić[1], Bojana M. Radojković[2], Marko D. Ristić[3], Ivana V. Vasović[4]

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Abstract:

The investigations of the turbulence in the flow are one of the most expensive, thus the improvement of existing ones and the research related to the new methods are in continual development. The multidisciplinary approach led to the application of the infrared thermography in the turbulent boundary layer observations with the endpoint goal of energy and cost savings in its early stages. This work presents the use of the industrial type infrared thermography for identification of the turbulent zones in the free convective flow, so far the less investigated problem related to convection heat transfer. It was shown that the transient spot temperature difference, measured on the complex geometry of the real-scale coal ventilation mill, of the Thermal plant "Kostolac B", by an infrared camera, is a good parameter for identification of the most influenced positions by turbulence. The defined fields with maximal transient temperature difference are in accordance with theory and values calculated by numerical simulations for clean geometry, confirming the assumptions. The described method is also convenient for use in cases when the other methods are not applicable because of the complex geometry, unapproachable, or for the other similar reasons. The results from this work would support the more precise measurements with the research type infrared camera, the other methods for measurements.

Keywords: turbulence, free-convection, heat transfer, thermography

1. Introduction

The flow created by heat transfer has been a focus of many researchers for decades, especially with the growing needs of industry, with the tasks even to reduce the consequences of turbulence presence or to manage and control the favorable turbulent flow. A final cause is a reduction of the expenses in at least one of the phases: from designing, through production to operation, and maintenance. The turbulence has been investigated by experimental, theoretical and numerical methods, because of what these observations are classified as the most expensive. The knowledge accumulated from the fundamental fluid dynamic and heat transfer researches [1-5] has supported a further explanation of the creating mechanism and the nature of the turbulent boundary layer to details, for both the forced and the free-convection flows, [6-10]. Development of experiences, theoretical and numerical methods, algorithms, IT and measuring devices from different branches of science and engineering have improved the turbulent flow investigations, qualitatively and quantitatively [11-12].

The thermal boundary layer at the forced flow and in the free-convective laminar flow was described, together with visualization of the free-convective flow around the hot vertical plate in [1]. The basic relationships and the dimensionless coefficients supporting the similarity analysis were described in [2], followed with the flow visualization over the simple body shapes.

Especially interesting for the present work are the investigations related to an examination of the time history of the temperature changes and the source of transient nature. In the researches [7-10,13] the time traces of the temperature changes were recorded and the characteristic temperature variation pattern inside the thermal boundary layer has been recognized as an impact of the turbulent spots and/or vortices creation in presence of forced convection. The temperature changes are more frequent and intense with a growth of the amount of the turbulent spots, beginning from the laminar flow, where changes are little or unrecognizable due to lack of the turbulent spot presence, to the turbulent zone which gradually follows the amount of newly formatted turbulent spots along the model contour *i.e.* local Reynolds number. The formation mechanism of the forced-convection turbulent flow has been investigated in a wide range of aspects. The free-convective flow has been observed throughout the analogy with the forced convective flow. The analyses of experiments, described in [10], have concluded that the heat and momentum transfer at free-convective flow are not analogous to the forced-convective flow. The authors in [10] emphasized that the characteristics of the free-convective boundary layer is unique in comparison to the others, what requests the specific scaling correlations. As the viscous sublayer at the free-convective flow is unrecognizable, the boundary layer is divided into the inner and outer layer, in relation to the maximal profile velocity position [10]. Further on, the free-convective logarithmic velocity profile does not exist in a zone commonly used for the forced convective flow (at a dimensionless wall distance $y^+>30$), while the temperature profile does follow the logarithmic law and the temperature fluctuations to reach their maximum at distance of $y^+ = 15$, according to the experimental results presented in [10].

In [4] the free-convection flow, analysis has been conducted through the visualizations. The various base cases have been presented, as follows: steady flow over the vertical/inclined plate, over the curved surfaces, the flow in enclosures, tubes, channels, *etc.* In addition, the cases of non-stationary – oscillated heat transfers have been investigated.

Nowadays, the investigations of turbulent flow are performed from the large - industrial to the micro-scales with various aims, for example, of determining the flow characteristics of the multiphase flow, optimization of the coal pulverization process of environmental protection [14,15]. For the listed flow investigations the numerical simulations have been used as the only method available for visualizing the flow pattern inside the ventilation mill, and determination of the turbulent nature of the multiphase flow. The impact of free-convection flow around the ventilation mill idealized geometry of the environment has been observed by numerical simulations also, while the research and industrial thermal-cameras have been used for input definition and verification of the numerically obtained temperature distribution over the housing surfaces [15-17].

However, the development and adoption of the new and economically efficient methods are the permanent tasks in the field. The infrared thermography has been introduced recently as easy-to-use, affordable method, implemented as an addition to the other standard methods in fluid dynamics investigations (visualization of the flow traces, thermal sensitive pints, *etc.)* for acquiring the broader perception of the phenomenon.

As the thermography is one of the methods for predicting the flow transition, through monitoring of the surface temperature changes, its advantage has been recognized and intended for the early stage investigations of the boundary layer due to its simple and efficient application [18].

This work presents the analyses of the experimentally obtained unsteady surface temperatures with the aim to justify application and convenience of the infrared (IR) thermography in order to identify the measuring places in the turbulent flow. The flow around the housing of the ventilation mill has been induced by free-convection, which by itself has been caused by unsteady heat transfer from the multiphase flow inside the ventilation mill. Hereby, the measurements have been conducted by the industrial thermo-camera FLIR E40, as an affordable measuring technique for the early test phases. The experimental object was the operating ventilation mill of the Thermal plant "Kostolac B". The results show that the IR thermography is a convenient method for the early stage investigations of the turbulent free-convection flow. Furthermore, the measuring spots of the flow parameters are selected in relation to the surface temperature values and their maximal root-mean-square (*RMS*) deviation.

2. Method

A method for positioning of the flow measuring devices, in the free-convective flow is mainly intended to contribute experimental savings and energy. Furthermore, this method would aim to cases when other measuring methods are hardly or not applicable for some reason (at unreachable or unsafe places, for instance). The core idea of the selection of the spot position in turbulent flow parameters' advanced measuring, PMS, is based on a determination of the spots at which the temperature fluctuations are the largest in the time history of recordings. It is a post-processing method of analyzing the thermograms.

To the purpose of this research, a term thermogram is related to the thermal video record, a series of thermograms, which are connected in a time sequence history.

On the contrary, to the forced convective flow, for which the gravitational effects are neglected, the free-convective flow is maintained from the difference of buoyant and gravitational force [1-4]. Furthermore, heat transfer is causing the temperature rise in a zone of a certain thickness of the heated wall, thus produce the density change in respect to the air at rest, far away from the heated wall. Similar to the behavior in the forced convective flow, the thermal boundary layer exists along the heated wall, which may have laminar or turbulent character, neglecting the heat transfer from the friction effects [1-4]. The free-convective similarity parameter Grashof number, Gr, in relation to the analogous square Reynolds number, Re^2, determines a type of the prevailing flow (free-convection in external flow prevails when $Gr >> Re^2$). Type of the boundary layer is defined with the local value of Gr_x, whereby $Gr \approx 10^9$ describes fully developed turbulent flow [1-5]

The IR camera lens receives emitted radiation from three sources from its surroundings, as follows: from the observed object (this one is a function of the object's temperature), from the object's surroundings (reflected from the object), and the atmosphere (a gray body which partially absorbing, transferring and radiating the radiation) [20,21]. The radiation energy emitted from the object, test model, is calculated as a difference between the total energy of the thermally ideal body, a "blackbody", at the temperature of the object and the energies emitted from the object's surroundings and the atmosphere. As non-ideal bodies, test model, surroundings and the atmosphere are in the energy equation corrected by the coefficients to effective values. Herein, the emission from the test model is a function of its temperature corrected for the emittance of the surface and transmittance of the atmosphere. The various sources, including the objects in the close surrounding, emit their radiation energy which then is partially reflected from the test model. The reflected energy is a function of the temperature of the objects in the surrounding of the test model (a common one), reflectance and transmittance of the test model. The atmosphere emits the energy proportional to its temperature, corrected for the emittance of the atmosphere and transmittance of the test model. The atmosphere fulfills the volume between the test model and the IR camera lens. It tends to weaken the emission due to the absorption by containing gases and scattering by fluid particles.

In this work, it was assumed that turbulence in the boundary layer, would lead to the thermal radiation ray diffraction due to intense and unstable density. Furthermore, the thermography has been applied as a method for visualization and measurement, analogous to the non-destructive flow visualization methods intended for application in flow conditions with at least 2% of density deviation (for instance the shadowgraph) [22,11]. Herein, for indication of the turbulence presence, it is important to note that recording of the emitted radiation has been done in an orthogonal direction to the flow through different levels in the boundary layer. The special care was carried out to prevent lens transverse movement due to vibrations from the ground. In this way, only single information about the surface temperature is captured, at a single place in a single moment, and it is dependent on the current flow conditions inside the boundary layer. Hence, the surface temperature would be different in two adjacent recording moments due to different flow conditions. It is assumed that the flow turbulence can be identified on the basis of the largest difference of the spot temperatures during the recording sequence. The placement of each particular spot with identified turbulence can be confirmed by comparing placements of two parameters, that are the root-mean-square value of the largest temperature differences, $RMS\ \Delta T$, and the corresponding temperatures in-place (maximal, T_{max}, minimal, T_{min}, or mean T_{mean}). Further verification has been made by comparison with the theory and experiments of the free-convective flow around the simple geometries from the literature.

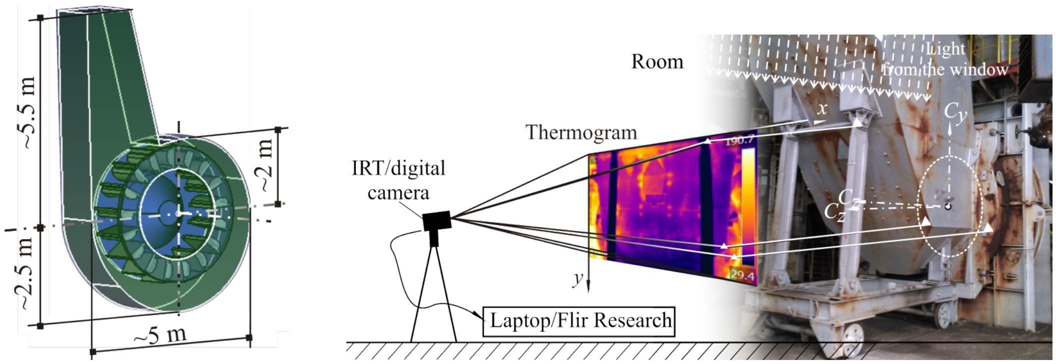
It may be expected to have some spots/zones with minor temperature differences. In these cases, it may be interpreted that the turbulence has the neglectable influence on the flow and that the uncertainty of the measurement has taken dominance due to a distance of local spot.

At first, the previously obtained flow parameters over the ventilation mill, VM superficies, from [15], were analyzed. Afterward, the global zones of the specific temperature intervals are overviewed, selecting the zones with the highest/lowest temperatures. Furthering, the measuring lines are selected in correspondence with VM superficial geometry, accounting the places with the expected higher level of turbulence in the flow (for example around the obstacles as are the fastening ribs, the flanges, the service openings, and the joints, *etc.*). In the end, several cycles of re-positioning and parameter checking are made to set up. Finally, for the series of temperature readings along with measuring lines, during the recording time, are reorganized, processed and compared.

The idealized VM geometry, cleaned from the details (wall thickness, insulation, ribs, etc.), has been created by the open source software FreeCad v0.16 [23], based on data from [14,16], aiming construction visualization, Figure 1 (a). The more detailed geometry was used for considering the temperature field by the numerical simulations [14-16]. In the later, wall geometry corresponds to the global real-scale measures, whereby the thickness of the side walls is 140 mm (without the insulation), and 20 mm from the front/back sides with additional thickness of the insulation of 40 mm) [15]. However, other details on the surface have been neglected in accordance with the assumed impact and the present task. The external geometry of the real scale VM is partially visible in Figure 1(b) as a part of the experimental setup.

The results from the numerical simulations from [15] have been used to localize the zones with the highest temperatures and the velocities, in which the turbulence is expected. The advanced numerical simulations in [15] have considered the heat transfer generated from the internal multiphase flow (gas with granular phase) through the VM walls, and further to the external environment. The multiphase model in the Euler-Euler approach has been implemented to the internal flow [15]. The artificial environmental temperature has been 20º C, the thermal boundary conditions were pre-calculated according to the average Nusselt number, and the input temperatures of each phase has been selected from the series of measurements [15].

In the experiments, the surface temperature measurements were conducted over the visible housing surfaces of the one VM, of the eight, at the Thermal plant "Kostolac B", Block 2, milling system. The mill no. 6., EVT N 270.45 type, was selected due to its recent maintenance. The VM's rotor is running with n_{rotor} = 400 rpm.



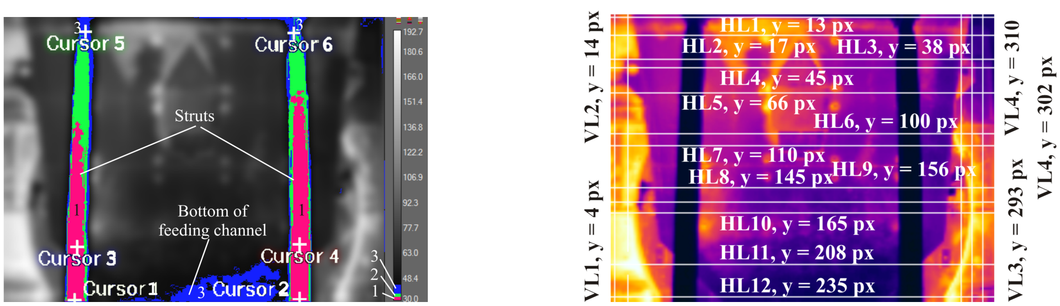
(a) Simplified internal VM geometry (b) The experiment setup

Fig. 1. The geometry of the VM and the experimental setup

In Figure 1 (b) the setup for the temperature measurements is shown. The IR camera FLIR E40 [21], fixed on the easel, was directed to the front side of the housing at a distance of about 7 m. At this distance, a single pixel represents about 15 mm of real scale lengths. The high-band range for measuring temperatures up to 650º C has been selected, while the camera has a thermal sensitivity of less than 0.07º C, the overall measuring error of about ±2º C, and the frame rate of 30 frames/s [20,21]. The environmental temperature during tests was 20º C, corresponding to the conditions adopted in the numerical simulations. Data recording was performed by the specialized software FLIR Research, while the analyses have been done with the FLIR Research and Tools software [24].

In this process, the open source software have been used too, as follows: NotePad++ v7.5.9. (data exchange and batch file writing) [25], SciDAVis v1.23 (managing and representation of the results) [26], gnuplot v5.2. [27], PaintNet v3.5.5 [28], and InkScape v3 (data visualization) [29].

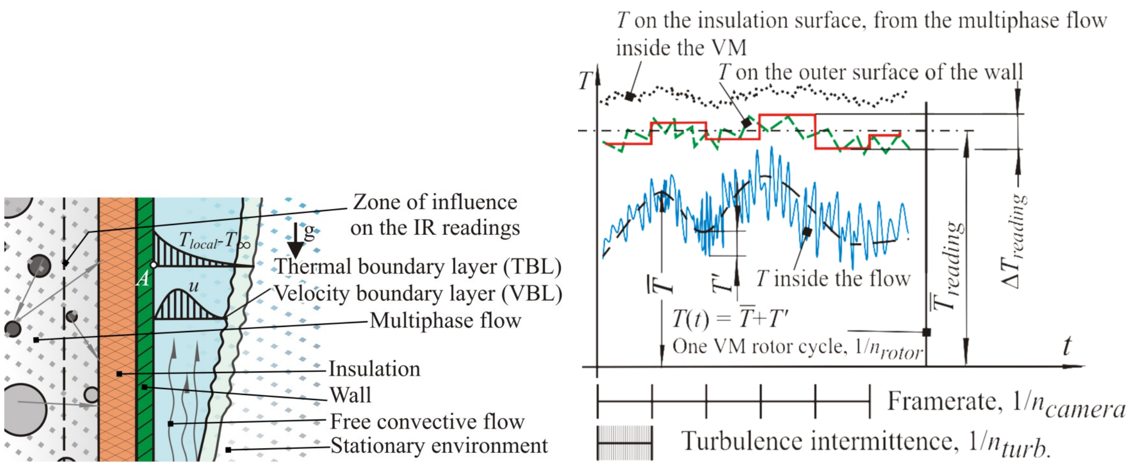
The six measuring spots are ordered along the support struts, Figure 2 (a), assuming the creep or no flow along struts. The five vertical, VL, and the twelve horizontal lines, HL, were selected by matching the locations of the maximal local T and geometry details on the VM front.



(a) The six measuring spots – cursors (b) The measuring lines in the front view

Fig. 2. The setup of the measuring places

During the process of heat transfer, from the multiphase flow to the environment, the source thermal energy is lost partially through the insulation and the walls, Figure 3 (a). The schematic view of the temperature transiency at different places is shown in relation to the VM rotor rotational velocity, Figure 3 (b). The advantage of the thermal camera application against standard boundary layer test methods (the Pitot tubes or the hot wire) is emphasized from here [11]. The advanced equipment for detailed measurements of turbulent nature would be inefficient and costly in the early stages of flow turbulence investigations due to numerous setup changes. Some of the contemporary methods, such as Laser-Doppler anemometer or Particle Image Velocimetry, would not be even applied in cases of industrial facilities such as the thermal plant [11]. Instead, location selection for future measuring of the flow parameters, by thermal imaging, would narrow the choices, and thus speed up the process. The actual experiments have been repeated for several times in the same position, with different duration of recording, but in this work, the singe selected case is presented in this work.



(a) Heat transfer from the multiphase flow to the environment

(b) The time scales of interest

Fig. 3. Scheme of heat transfer and different temperature time-histories

4. Results and Discussion

The calculations in [14-16] have shown that the flow around the VM is free convective with the turbulent boundary layer, according to the reported Grashof number order of magnitude of 10^{12}. On the foundations of the static temperature distribution outside the VM, in [15], that represents the thermal boundary layer, TBL, spread in a vertical plane, the TBL over the front side of the VM has been assumed for a clear configuration, Figure 4. In Figure 5., the selected zones near the left and right side of the flange on the VM housing are compared, both presented in photos and thermograms. The measurements after renewing the insulation are in a good agreement with the results from [15,16]. The IR camera is capable to sense and record the temperature changes sourced from the VM wall interior, but the insulation and wall have blurred the heat transfer and decreased the temperature value for about 10º C [15]. On the left side, under the level of the rib and around the sides of the flange, the highest temperatures occurred, in-between T_I = 190.7º C – 150 º C. A second highest temperature zone is located upwards from the rib to the flange side, a zone with the high temperatures at the flange involucre, near and around the ribs, and the most heated, at the lower left zone, where the hottest zone corresponds to the most heated zones inside the interior multiphase flow [15,16].

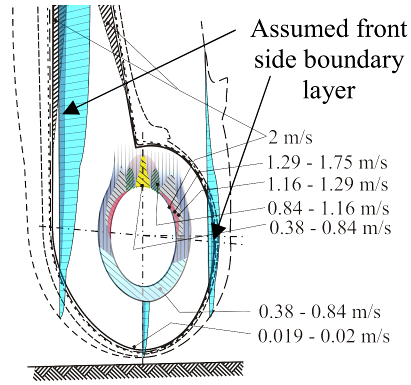


Fig. 4. Composite image of calculated and assumed boundary layers [15]

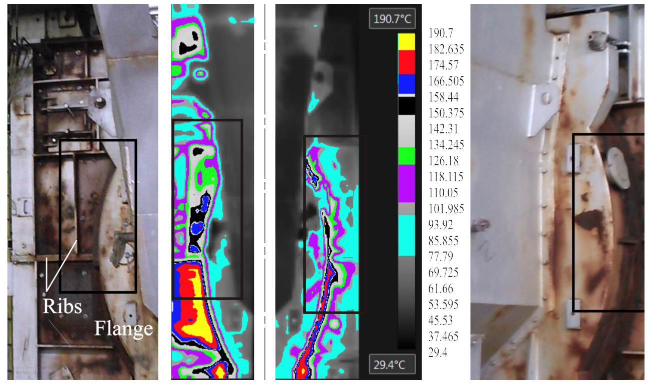


Fig. 5. Zones of interest for turbulence observation

The surface temperature, its statistics, and the largest local value of the ΔT = T_{max} - T_{min}, measured on the struts are shown in Figure 6. The calculated value of the struts' local Rayleigh number is 3.5E+11, at a distance of 0.7m from the bottom (at spot C4 with the lowest $\Delta T_{C4} \approx 0.3$), indicates the turbulent BL presence over the struts. The struts are at the lowest temperature and the ΔT_{C4} is the lowest in the actual thermogram, also.

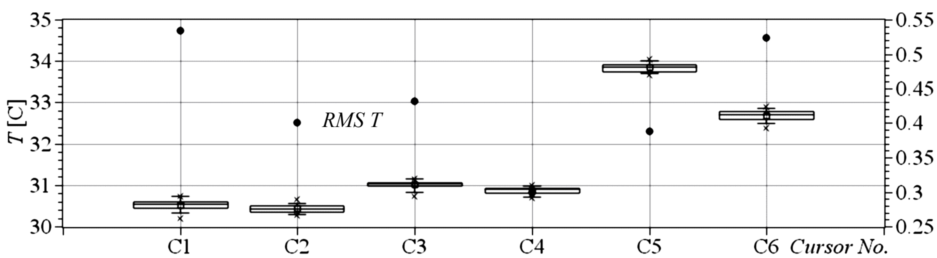
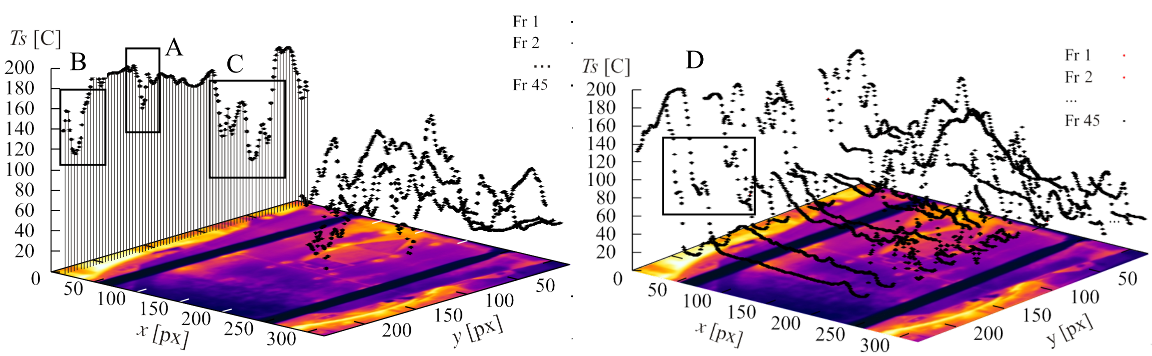


Fig. 6. The temperatures and *RMS T* at the six spots measured on the struts

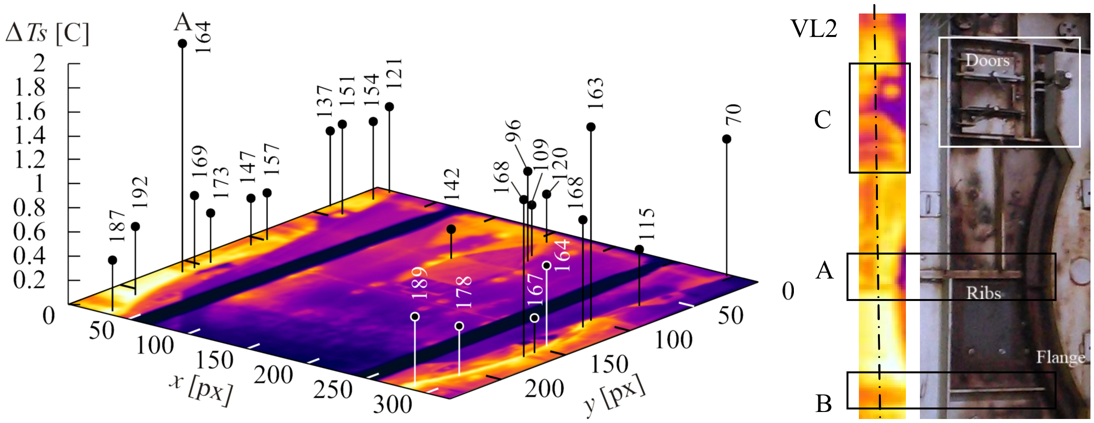
The temperature distribution along the selected horizontal and vertical lines is shown in Figure. 7. The measured values were analyzed in accordance with the geometry. In Figure 7 (a) the fields on the left side, along VL2, signed as "A" and "B", corresponds to the temperatures measured over the ribs on the construction, while a field "C" corresponds to the positions of the maintaining door linkages. Along the horizontal lines, the temperature changes with picks, inside the field "D", occurred due to the boundary layer presence around the flange's sides.



(a) Five vertical acquisition lines (b) Twelve horizontal acquisition lines

Fig. 7. The static temperatures on the wall measured along selected lines (in recording duration)

Further, analyzing the ΔT at every pixel along the horizontal lines, in recording time, showed the places with maximal values which do belong to very different local temperatures, Figure 8.

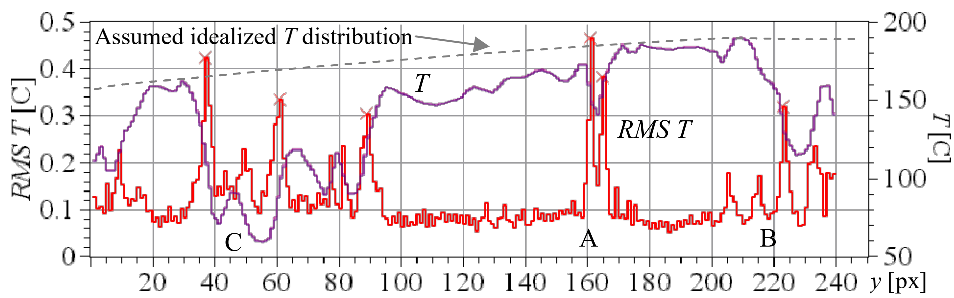


(a) ΔT_{max} over the thermogram (b) T_{local} – photo

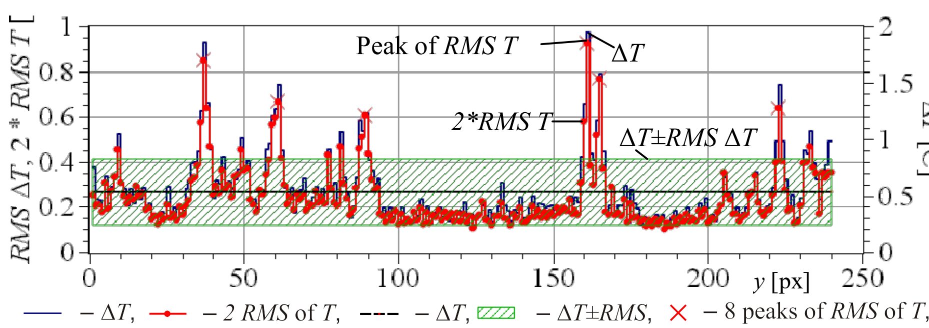
Fig. 8. The maximal temperature differences along the horizontal lines (in recording duration)

The spots with ΔT_{max} are all located in the fields with the assumed highest turbulence levels (viewing from the front), such as the spots near the ribs, along the flange circumference and above it, and the few points at the coal dispenser. The placements of ΔT and T values on the left and right sides are in accordance with calculated values for ideal VM geometry (Figure 5.), and in correspondence with the literature [1,2,4,7]. The temperature drop occurs over the ribs' tip due to less transferred heat along ribs' length. The temperatures just above and below ribs are higher due to the presence of the vortices in corners (VM front side – rib). A similar distribution is seen on the right side, but less in magnitude.

The comparison of the local distributions of T and *RMS T* along the VL2 (at x = 14 px) is shown in Figure 9 (a), while the comparison of the ΔT, mean value $\Delta\overline{T}$, *RMS* ΔT, and the double *RMS T* are given in Figure 9 (b). Comparison of the T drops and appearance of the maximal *RMS* ΔT values was interpreted as a good indicator of the exact spots in which the maximal level of turbulence occurs, found in the fields "A" – "C" as follows y_B = 225 – 235 px, y_A = 162 – 168 px, and y_c = 38 px – 45 px, 50 px– 62 px and 80 px– 90 px.



(a) Comparison of the local temperature distribution and *RMS* of temperature



(b) Comparison of the placements of various temperature parameters

Fig. 9. The comparisons of T parameters from the record R200 along VL2 (at x = 14 px)

4. Conclusions

The presented method for ordering the turbulence measuring places, applied to the industrial facility, showed a good correlation with velocity distribution from previous investigations and the theory. The IR measured local temperature deviation compared with local temperature, over the time history is a good parameter for indication of the turbulence existence in a flow field. The equipment and time costs as well as the efficiency of the IR thermography, as a method for identification of turbulence zones, are affordable and adequate in the cases when other methods are not available or applicable. The IR thermography is intended and justified for the early-stage observations. Further, for results that are more precise, the high-speed and high-resolution IR camera type is recommended.

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