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Study of high temperature thermal boundary conditions on active surfaces of the cylinder shaped ultrasonic transducers

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Abstract

Results of an experimental and numerical research of two-dimensional unsteady flow around the butt end of the model of cylinder shaped ultrasonic transducer at zero angle attack are presented. The flow formed employing linear dc plasma torch, is turbulent with *Re* number between 1.8×10^4 and 2.2×10^4 and temperature −1200 K. At this regime the flows boundary layers at the cylinder edge separate laminar and transition takes place in the free shear layers. In the shear layer strong vortex shedding and temperature fluctuations are observed. Experimentally estimated distribution of velocities and temperatures on the flat surface of circular cylinder compared with the predicted and has been established good agreement under the results. The influence of the location to distribution and quantity of dynamic and thermal parameters was investigated.

1. Introduction

Determination of integral and pulsating characteristics of high temperature gas flows is necessary for investigation of high temperature turbulent flow dynamics, heat and mass transfer. Plasma Processing Laboratory of Lithuanian Energy Institute has developed an acoustic method for investigation dynamic characteristics of high temperature flows and jets employing ultrasonic transducers. For diagnostics of the high temperature and plasma flows, the selection of forms, cooling regimes and orientation of the working surfaces of primary transducers is very important. It is widely known, that the whole set of characteristics at the active transducer surfaces is distorted, as with the temperature increase new phenomena occur influencing measurement conditions and accuracy [1,2]. The thickness of thermal (δ_t) and dynamical (δ_d) boundary layer may have a significant influence on determined flow characteristics. Due to the dynamic and thermal boundary layers conditions, some fluctuation may be introduced in the flow between two ultrasonic transducers. Therefore that fact may cause some difficulties in determination of flow parameters with the view of qualitative results. So we have met a problem how to evaluate the influence of boundary conditions on the accuracy of cylindrical shaped ultrasonic transducers for high temperature flow diagnostics.

Ultrasonic transducers, immersed into high temperature or plasma jet of different configuration, appears as two cut cylinders located vis-à-vis in the flow. In this case the numerical investigations solving Navier–Stokes and energy equations for the boundary layer would be the best approach [3]. So far it is not possible. Half-empirical methods also are not helpful in increasing accuracy, because application of mathematical models gives no evaluation of the temperature factor, of the secondary flow in the flow separation zone at the transducer surface, flow reattachment, the cooling efficiency effect, etc.

The study of turbulent flow around a finite circular cylinder was of the interest many years ago. Some researchers also have published experimental and predicted results for the cylinder immersed into high temperature jet. Unfortunately related investigation of

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Nomenclature

c_p	specific heat (J/kg K)
G	flow rate (kg s^{-1})
q_z	heat flux along z axis (W m^{-2})
R	cylinder radius (m)
T	temperature (K)
x, y, z	dimensional Cartesian coordinates (m)
Greek symbols	
a	thermal conductivity coefficient (W/m K)
δ_d	thickness of dynamical boundary layer (m)
δ_t	thickness of thermal boundary layer (m)
ρ	density (kg m^{-3})
w	dimensional velocities in x-, y- and z-directions (m s^{-1})
Subscripts	
d	dynamical
t	thermal

flow around the butt-end of the cylinder has not found in sources of scientific-technical literature. The most close to the present topics appears the proceeding of [4] concerned an experimental investigation of the flow around circular cylinders joined with a step.

On the other side, the flow over a free end of the cylinder maybe is similar to the flow over a circle shaped flat plate or disc. Difference may occur in the reason of possible flow along the generatrix of the cylinder and flow separation in the entrance region of the surface. The evaluation of the flow caused of the end edges effect is also required. It is important also acknowledge that the plasma is the activated state of medium where the individual types of particles, e.g. ions, electrons and neutrals (in the form non-excited and excited atoms, molecules and radicals), can be grouped in accordance with different temperatures. The reaction in the plasma depends on the temperature and on the concentration of activated species reaching the surface from plasma. So that fact may influence gas dynamic and heat transfer characteristics on the surface.

At least it is known [5] that distribution of parameters in high temperature jet and flow differs from the distribution in ambient temperatures. Due to the difference of enthalpy of heated jet and ambience, the flowing regime and gas composition, distribution of parameters may differ substantially. So it has been essential to perform investigation in high temperature conditions.

Therefore, the purpose and the main task of the present work is using experimental and numerical methods to investigate gas dynamic and thermal characteristics in the flow over the transducer end and to establish their influence on the measurement accuracy.

2. Numerical solution

We have developed a numerical simulation of gas dynamic and heat transfer in order to link the transport phenomena on the free end of finite cylinder. The "Fluent" software has been used to solve Navier–Stokes and energy equation based on the dynamic k–ε model for the fluid jet in the space around the free flat end of the cylinder. The system was assumed to be axisymmetrical and the fluid flow turbulent. It corresponds to the presentation in Fig. 1. According to the conception of thermal boundary layer, there was postulated that all changes in a thermal process are intramural and close to the surface ($\partial t/\partial z \neq 0$ inside and $\partial t/\partial z = 0$ outside boundary layer). We have also concluded that $\partial^2 t/\partial y^2 = 0$, since the thermal boundary layer is very thin in the cylinder end region. So the energy equation assumed the conformation as

$$w_y(\partial t/\partial y) + w_z(\partial t/\partial z) = a(\partial^2 t/\partial z^2), \tag{1}$$

where

$$a(\partial^2 t/\partial z^2) = -(\partial q_z/\partial z)(1/\rho c_p). \tag{2}$$

As closing Eqs. (1) and (2) the equation

$$w_y(\partial w_y/\partial y) + w_z(\partial w_y/\partial z) = v(\partial^2 w_y/\partial z^2) \tag{3}$$

and

$$\partial w_y/\partial y + \partial w_z/\partial z = 0 \tag{4}$$

were used.

Radiation exchanges were not included, because of low temperature of the cylinder (it was intensive cooled).

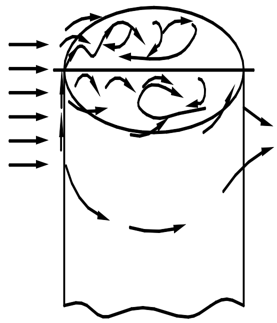

Fig. 1. Primary flow model on the free end of the cylinder.

The other typical boundary conditions were as follows: (1) constant temperature of fluid flowing on the entrance of the surface; (2) zero normal gradients at the inflow; (3) rectangular distribution of velocities temperatures; and (4) constant of the inflowing jet turbulence (3%) [6].

Two different *t*-type orthogonal grids have been used. To avoid any kind of wall functions, the boundary layer is resolved by extremely fine grids in the near-wall region and no-slip boundary conditions are applied. The simulation aims to predict the flow and temperature distribution of high temperature air in the near-target boundary conditions. The size of the computing domain is 200×200 mm and the total number of grids is 388782.

3. Experimental apparatus and technical details

All experiments were performed in a high temperature air jet, generated of plasma torch. The model of cylindrical shaped ultrasonic transducer (Fig. 2) has manufactured and tested. It appears as water-cooling finite copper cylinder with flat end of 25×10^{-3} m diameter and 45×10^{-3} m length. The model was located in the cross flow of heated air in 35×10^{-3} m distance from exhaust nozzle of plasma torch so that axis of flat end of the cylinder and axis of heat temperature jet were in coincidence and the gas flows parallel to the flat surface.

The linear dc plasma torch 250 kW of power with hot cathode and step-formed anode were used for heating air jet [7]. It consists of a cathode junction with tungsten cathode, cathode-coupled section for arcing, diffuser, insulation rings, and step-formed anode.

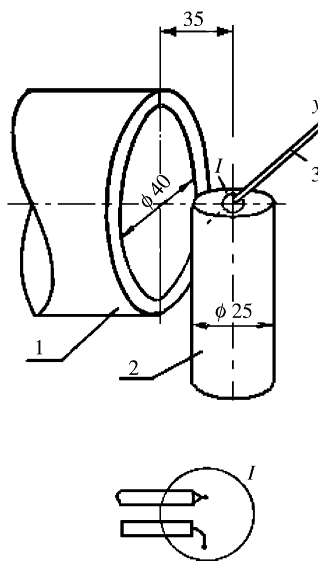

Fig. 2. Schematic presentation of experimental installation.

The 0.4 m long nozzle and a confuser were used for plasma stream stabilization. High temperature air jet parameters were settled and regulated as constant in experiments described here. The flows and heat parameters considered here were investigated by means of velocity, temperature and heat flux measurements employing hot-film anemometry, microthermocouple and calorimetric measurement techniques. The Reynolds number, based on the cylinder diameter, lay between 1.8×10^4 and 2.2×10^4, temperature -1200 K. The surface temperature was measured and found to be 340 K. This temperature was also imposed in the simulation instead of the flux density.

Local values of the flow temperature were determined with the help of the platinum-platinum/rhodium microthermocouples with electrode diameters up to 30×10^{-6} m, and the velocity was measured using the thermoanemometer with the film gauge produced by the Thermo Systems inc. Flow and plasma torch parameters were determined using conventional and laboratory created methods and devices. The beginning of the Cartesian coordinates is the intersection of circle symmetry axis on the flat surface of the cylinder. Measurements performed at the following steps: *x*—starting from -15×10^{-3} m by step 1×10^{-3} m until $+15 \times 10^{-3}$ m; *y*—-15×10^{-3} m by step 5×10^{-3} m until $+15 \times 10^{-3}$ m; *z*—0 by step 5×10^{-3} m until $+15 \times 10^{-3}$ m.

4. Results and discussion

As concerns the initial flow and gas temperature, a preliminary study showed the complexity of the configuration of the flow dynamic and boundary layer at the flat end of the cylinder. The "Fluent" software was an excellent advisor in our further experimental research. Streamlines and temperature distribution predicted by the model in the near-wall zone are plotted in Fig. 3 for $T = 1200$ K, $w = 65$ m s^{-1}. Accordingly to the "Fluent", the distribution of temperature along the axis perpendicular to flow shows that the maximum values of δ_t and δ_d is on the axis of the flow coaxial with the cylinder. Flow temperatures and velocities profiles are flat and filled better at the edge of the external circle. This indicates high intensity of heat exchange between the cylinder end plane and the high temperature gas flow. Two low temperature zones have been observed near the front and tail edge of the flat surface of the cylinder (Fig. 3b). The first of them may hold influence to the forming boundary layer; the second may hold the low influence to the measurement results.

We conclude that plasma jet characteristics near the flat end of cylinder also depend on following factors: (a) plasma jet inflow parameters; (b) gas composition; (c) cooling intensity and water injection. The gas injection location and flow rate has also an important influence to

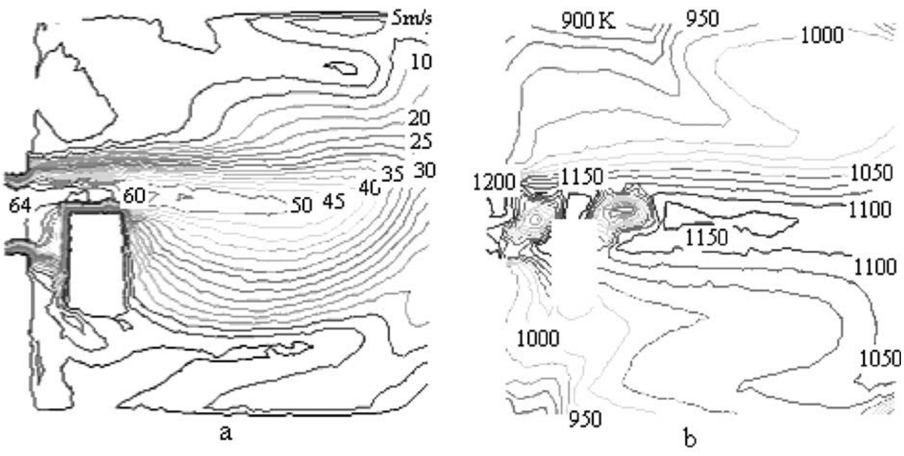

Fig. 3. Diagram of constant velocity (a) and temperature (b) lines around the finite circular cylinder.

shape and dimensions of profiles. In presented case when the flow rate of air $G \leqslant 28 \times 10^{-3}$ kg s^{-1}, the flow separation has also strong influence.

Results in Fig. 3 show that the middle region of the flow is two-dimensional for ratios $z/d > 0.5$. The separated region in the front of the flat end of the cylinder is characterized by the appearance of a quasi-regular distribution of vortices between central axis and edge of the circle.

The character of flow formation around the flat surface of the cylinder best illustrates Fig. 4. Measured results on the distribution of velocities and temperatures on the end of the cylinder have certain features comparing to the results for flat plate. In the case of intense cooling of flat plate, jet velocity and temperature near the wall is gradually dropping. In our case the drop of parameters is very sudden in the first half of the flat and almost constant on the other. This fact could be clarifying employing the flow separation and reattachment. The structure of flow and temperature distribution near the surface of ultrasonic transducer model shows the location of separation and reattachment lines. The separation line forms an arc matched to the rim of the cylinder; the reattachment line form also an arc, but bigger in radius, spreading toward the cross of x axe and the sharp edge of the circle. Profiles of parameters across the flow direction inside the interval between separation and reattachment lines are parabolic shaped with the camber pointed to the central axe of the surface. So, the maximal values of temperatures and velocities in the first half of the surface are situated around the external circle of it. In the backside of the surface they are substantially shifted up to wake zone.

Longitudinal temperature profile is deformed substantially when the distance z/R is less (Fig. 6). It is important to notice, that in a number of cases (exactly not defined reasons) the second separation on the surface has been observed. The location of its line is the backside of the flat surface in distance of $0.6 \leqslant x/R \leqslant 0.75$ from the centre (Figs. 4–6). The shape of the separation lines supposedly is approximated to the line or arch of large diameter.

The distribution of velocities and temperatures across the flow direction is parabolic shaped. Parameter values depend also on the distance from the surface. At the fixed distance $z/R < 0.02$ temperatures curve is rising all the time before coordinate reaches the end edge of the plate (Fig. 7).

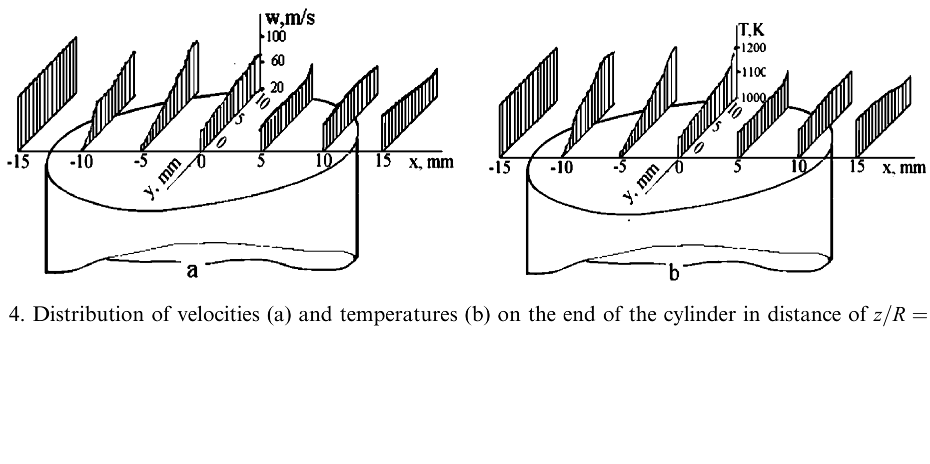

Fig. 4. Distribution of velocities (a) and temperatures (b) on the end of the cylinder in distance of $z/R = 0.04$.

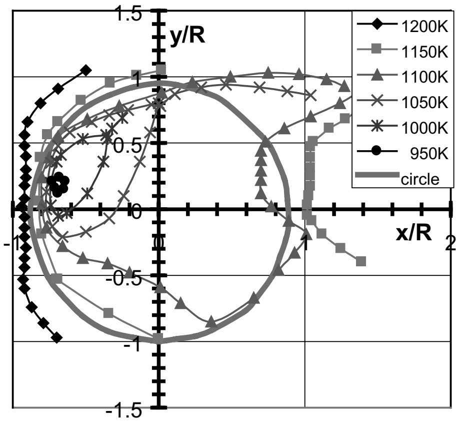

Fig. 5. Field of isotherms and temperature gradient on flat end of the circular cylinder in distance of $z/R = 0.04$ from the surface.

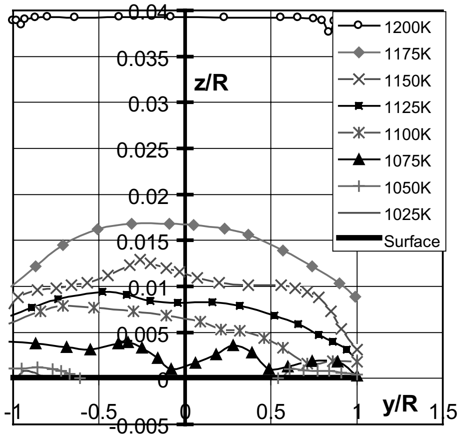

Fig. 6. Field of isotherms and temperature gradient near the flat end of the cylinder ($y = 0$).

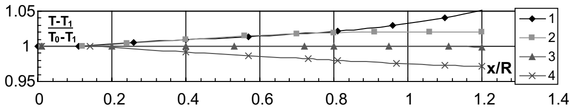

Fig. 7. Distribution of temperature near the flat surface of the finite cylinder $x = 0$, z/R, respectively: (1) 0.008, (2) 0.024, (3) 0.08, (4) 0.16.

The thermal regime inside measurement base of ultrasonic transducers plays a major role; accordingly the significant attention was paid to the distribution of temperature. The maximal temperature gradient on the surface forms in the front near the ambient of circle approximately coincidental to the reattachment line (Fig. 5) and the ultimate processes in change of temperature profiles follows near the wall (Fig. 6). Consequently the temperature gradient in the distance of z/R is most extremely and configuration of the field has a miscellaneous character. When $z/R > 0.2$, the temperature gradient and configuration of the field takes the stabile shape.

Results on the distribution of velocities and temperatures near the butt-end of the cylinder shows that maximal values of boundary layer thickness are located in the region of flat surfaces along the jet axis. It is visible, that parameter profiles are well filled and so much better when the distance from the wall is less. This means that heat exchange between the surface and jet is very intense in this region. Measurements and prediction for establishment of the change of δ_d and δ_t has been performed in z-direction. It has been found that in the centre of the flat end of the cylinder velocities profile became to full stability at $z/R = 0.3$ and the temperatures at $z/R = 0.25$ (Fig. 8).

The boundary layer thickness is unstable along the axe because of flow separation, reattachment, circulation and shear flowing. The regular increasing of boundary layer thickness starts only approximately from the middle of the flat end. Transition of temperature and velocity from their boundary layer values to the steady flow values pass asymptotically. Thus the influence of the flow to the mutation of the ultrasonic signal includes the entire operating surface. So we have a possibility to conclude that our ultrasonic transducers have to be oriented strongly perpendicular to the flow. Otherwise the character of boundary layer flow over the free end of both cylinders strongly changes so that there

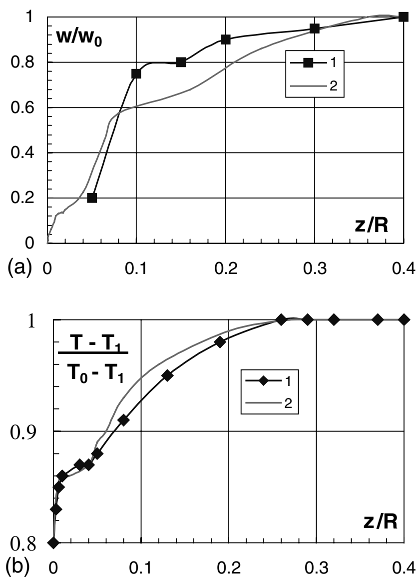

Fig. 8. Distribution of velocities (a) and temperatures (b) in the boundary layer a vortices zone of the flat end of the cylinder. (1) Experiment, (2) prediction. $x/R = 0$, $y/R = 0$.

appears flow separation on one of them and disappears on the other.

5. Conclusions

1. The flow around a butt-end surface of the finite cylinder appears as separated, convoluted and complicated. Flow separation begin in the front of the cylinder flat and continues up to the $x/R = 0.45$. The line separation is coincident to the edge of the circle flat.
2. Profiles of temperature and velocities inside of the separation zone, in the distance of $z/R = 0.025$ are parabolic shaped containing values corresponding to the minimal values of axial-flow in the flat end of the cylinder.
3. The maximal thickness of the boundary layer including thickness of eddies zone, makes $\delta_d = 0.35z/R$ and $\delta_t = 0.25z/R$. This is less than 10% of the basis length of ultrasonic transducers. The boundary condition on the ultrasonic transducer surface has only low influence on measurement accuracy. Thus the main error in temperature and temperature fluctuation measurements amounts less than 3%.

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