Numerical and Experimental Studies of Laminar Natural Convection on a Horizontal Cylinder

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Abstract This work deals with numerical and experimental studies of specific issues of natural convection flow around horizontal cylinder in the space limited by rectangular cavity. Physical models of laminar unsteady flows have been used for numerical calculations of heat transfer coefficients of four different diameters of horizontal cylinders and for several temperature gradients. The boundary conditions on the cylinder surface were defined by constant heat-flux. Procedures and results of the experimental studies are contained in the next section. All results were compared with different authors and different approaches. However the Nusselt numbers can be estimated due to the temperature interval, the results indicate need for further investigation

1 Introduction

Heat exchangers and their high effectiveness are very important for storing heat energy. They are often made from horizontal or nearly horizontal circular cross section profiles where is desirable to determinate their performance as accurately as is possible. However, the task of the analytical solution of the local heat transfer coefficient on the surface of heat exchangers with complex shape of the cross section is difficult to solve full equations of motion and energy together. The angle between the gravity vector and the tangent of every point on the surface curve varies along the fluid flow direction. This can bring a lot of problems even for current numerical methods. Even so this was investigated by various authors in a wide range of parameters to obtained correlation equations. The most frequently used empirical correlation equations of the authors Morgan, V. T. [1], Collis, D. C. - Williams, M. J. [2], Kreith, F. – Black W. [3], Churchill, S.W. - Chu, H.H.S. [4], Jaluria, Y. [5], Fand, R. M. - Morris, E. W. - Lum, M. [6] and finaly Brdlik, P. M. - Kuptsova, V. S. - Malinin, V. G. [7] are chosen for comparison with the data obtained by numerical and experimental investigation of a particular case.

2 Investigations

If the temperature of the surface T_w [K] within of a fluid is different than temperature of the ambient T_∞ [K] the thermal boundary layer occurs around the surface. Due to the buoyancy forces the fluid begins to move and a momentum boundary layer occurs. When the heat transfer caused by conduction of the fluid is compared with the heat transfer caused by convection the Nusselt number is obtained. For a horizontal cylinder surface, for a dimensionless temperature gradient and for a normal length to the surface the average of Nusselt number on the cylinder surface can be written as

$$\int_0^{2\pi} \left. \frac{\partial\left(\frac{T_w - T}{T_w - T_\infty}\right)}{\partial\left(\frac{n}{D}\right)} \right|_{n/D=0} d\theta = \frac{\overline{\alpha}\, D}{\lambda_f} = \overline{Nu}_D , \qquad \text{[-] (1)}$$

where *n* [m] is a normal length to the cylinder surface, *D* [m] is the cylinder diameter, θ is the angular coordinate around the cylinder. $\overline{\alpha}$ [W·m^{-2}·K^{-1}] is the average value of convection coefficient and λ_f [W·m^{-1}·K^{-1}] is thermal conductivity of the fluid. The main task for an investigation of natural convection on the outside wall of a body immersed in a fluid is in determination of the heat transfer coefficient.

2.1 Numerical investigation

For numerical investigations were used four different cylinder diameters and for solving was used CFD (Computational Fluid Dynamics) program Fluent version 6.3. The physical 3D model representing real case is placed in gravitational field defined by gravitational acceleration. The model represents the lower part of stratification builds with limited space around the heat exchanger tube. The basic geometry of the model with boundary conditions is shown in **Fig. 1**.

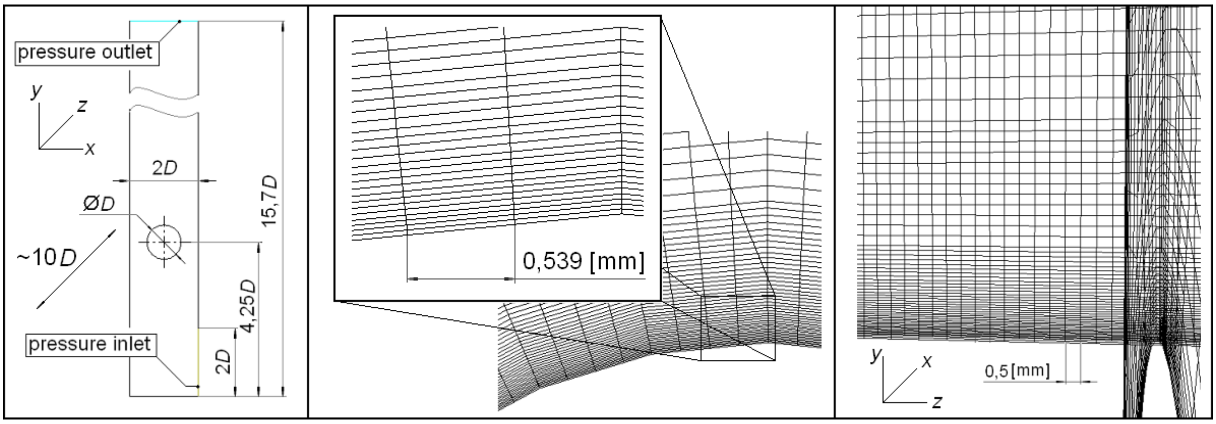


Fig. 1 The basic geometry of the model with boundary conditions related to the diameter of the cylinder and with preview of the grid on the cylinder wall (dimensions are chosen for diameter of cylinder *D = 0,022* [m]).

An incompressible fluid flow was considered with an unsteady implicit algorithm related to the Boussinesq approximation. On the surface of all four cylinder diameters were considered constant heat fluxes to obtain six approximate values for thermal differences between the cylinder walls and the ambient.

2.2 Experimental investigation

In this section is a very brief description of the measurement procedure. For heating of the fluid was used a horizontal copper tube commonly available on our markets manufactured according the standard EN 1057 with outer diameter *D* = 0.022 [m] and wall thickness 0.001 [m]. The temperature measurements were realized by five thermocouples (2 x 0.2 [mm], type “K“) inside of the tube wall and located on the whole perimeter in the middle of the tube length, **Fig. 2**.

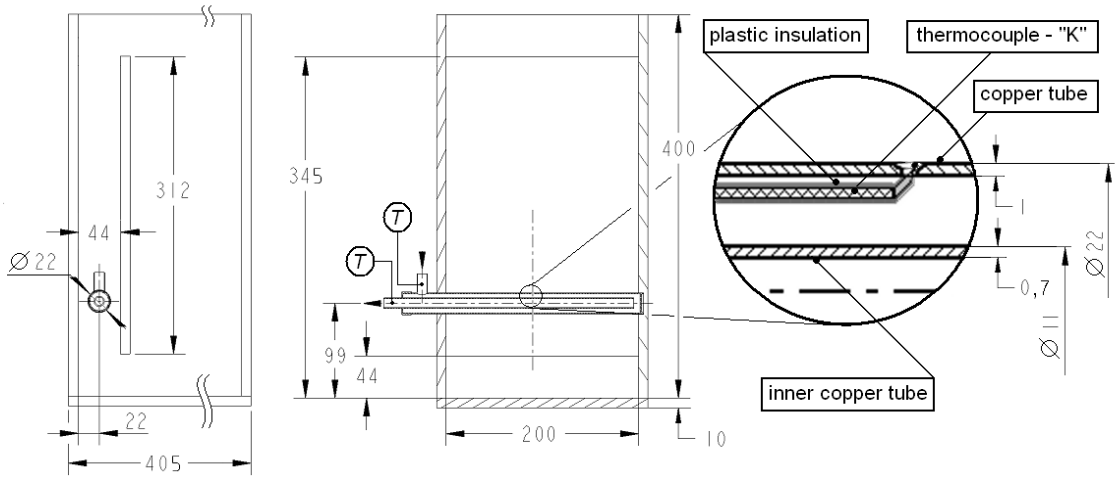


Fig. 2 The geometry of the model and the measurement set-up used for experimental determination of the heat transfer coefficient during free convection near the horizontal cylinder.

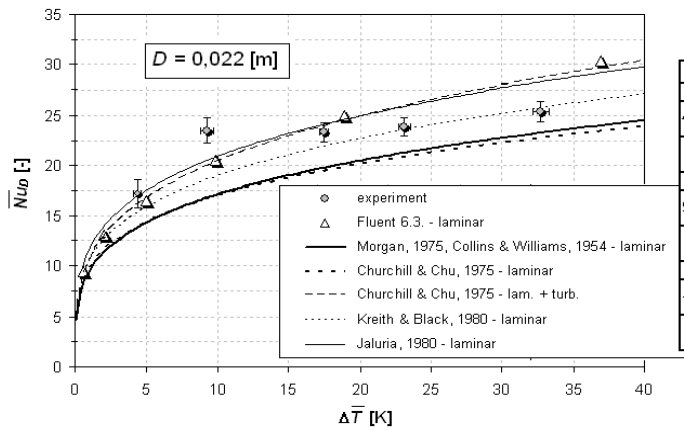
Another water circuit was used for the heating of the tube with an inlet and an outlet according the **Fig. 2**, where other two thermocouples and a rotameter ensured the data for performance counting.

3 Results

The value of Nusselt number relative to the horizontal cylinder surface can be determined by the equation (1). Regarding to the specified boundary condition of the constant heat flux on the surface, heat transfer coefficient can be defined as a ratio of the heat flux and temperature difference between an average temperature of tube wall and the ambient fluid and it can be written as

$$\overline{Nu}_D = \frac{1}{\tau}\int_0^{\tau} \frac{\dot{q}\, D}{\lambda_f\left(T_{AW}(\tau) - T_\infty\right)}\, d\tau \Rightarrow \frac{1}{\tau}\sum_{i=\Delta\tau}^{\tau} \frac{\dot{Q}_i}{\pi\, l\, \lambda_f\left(T_{AW}(\tau)_i - T_{\infty i}\right)}, \qquad [-]\ (2)$$

where τ [s] is the time of the process, $\dot{q}$ [W·m^{-2}] and $\dot{Q}$ [W] are the heat fluxes from the wall, l [m] is length of the cylinder surface, $T_{AW}(\tau)$ [K] is the average temperature of the wall in every time-step.



Experimental results:

ΔT [K]	5	10	20	25	40
$\Delta\overline{T}$ [K]	4,3 ± 0,3	9,3 ± 0,4	17,4 ± 0,3	23,1 ± 0,3	32,7 ± 0,3
Relative error	6,93%	4,78%	1,82%	1,60%	0,92%
$\dot{Q}$ [W]	28,1 ± 1,3	83 ± 3	153 ± 6	208 ± 9	312 ± 14
Relative error	4,52%	4,09%	4,06%	4,24%	4,33%
$\overline{Nu}_D$ [-]	17,2 ± 0,8	23,3 ± 1,3	23,3 ± 1,0	23,9 ± 1,2	25,4 ± 1,1
Relative error	8,24%	5,49%	4,12%	4,19%	4,10%

Fig. 3 The average Nusselt number relative to the temperature difference between cylinder surface and ambient water.

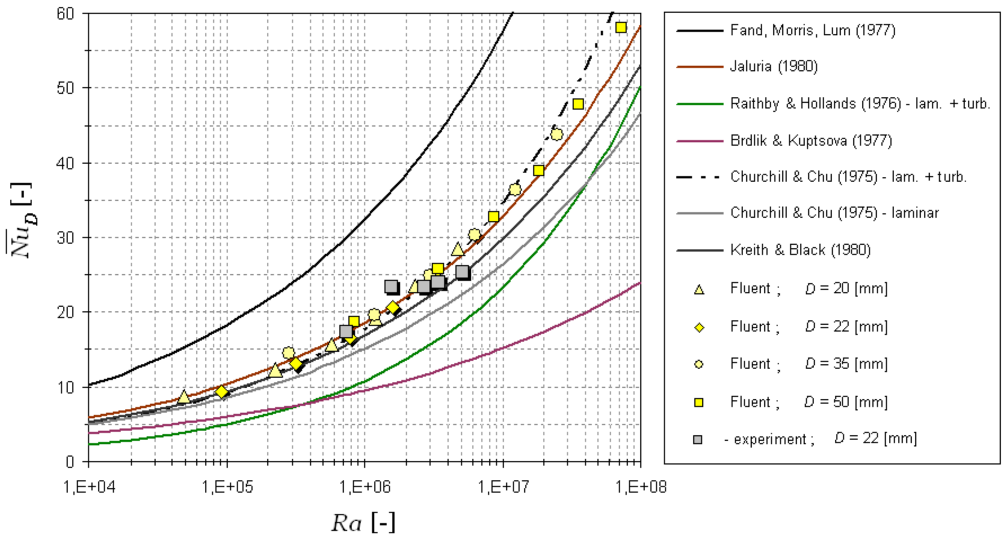


Fig. 4 The data of average Nusselt numbers obtain from the numerical simulation and experimental investigation against Rayleigh numbers compared with results of different authors.

4 Discussion and Conclusion

In the numerical investigations of the physical model of the real problem was made twenty-four laminar flow calculations for four different diameters of the horizontal cylinder. The experimental investigation was made for five approximate temperature differences between the cylinder surface and the ambient water. In the **Fig. 4** are shown results obtained by numerical and experimental investigations compared with results of chosen authors. Obtained results are within the laminar range for $Ra < 10^7$. All these empirical correlation equations of various authors compute with a constant temperature of the surface, only Brdlik - Kuptsova (1977) [7] consider constant heat flux.

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