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Modeling of Heat Transfer Passive Chilled Beam Compilation of Mathematical Model for Increasing Cooling Capacity for Passive Chilled Beam by Optimizing his Geometrical Parameters

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***Abstract* – The paper is focused on the research passive chilled beam. As a model passive chilled beam was selected four pipe passive chilled beam. On the basis of a mathematical model of passive chilled beam simulation program was created in Excel. In simulations of cooling power depending on construction parameters (spacing ribs, rib height and thickness, diameter and number of tubes) in the temperature gradient was found as the various construction parameters affecting the cooling power of passive chilled beam.**

***Keywords* – Cooling Power, Mathematical Model, Passive Chilled, Simulation.**

I. INTRODUCTION

The passive chilled beam is actually a ribs pipe heat exchanger in which cooling water runs. The convector is set under the roof but a minimum length must be half of width of the convector. A warm air in the top part of the convector is being cooled, it is being fell naturally.

Nowadays cooling convectors show a relatively small cooling power due to their length, leading to the need to increase their cooling power through adjustments to their structure or by selecting the appropriate temperature gradient or variations in the flow of coolant, thereby also increasing the cooling power without modifying its structure.

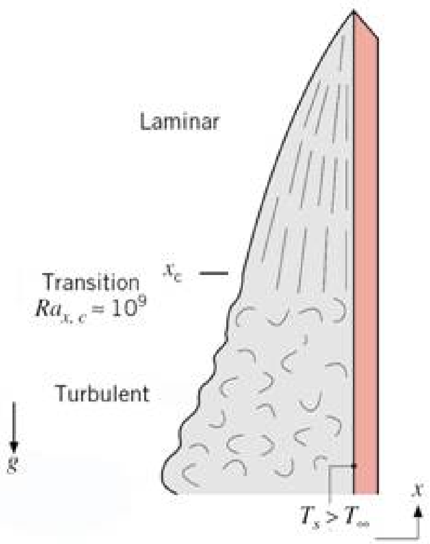

Fig.1. Boundary layer laminar and turbulent free convection on vertical plate (rib).

Air movement is caused by the change of its density and the resulting temperature changes in the flow. Natural convection flow as all that may be laminar or turbulent as shown in (Fig. 1), which is displayed laminar and turbulent convection off boundary layer of vertical plate [1]. Cooling performance is dependent on the temperature gradient, temperature gradient between the mean temperature of cooling water and ambient temperature, and especially from its geometry, especially the spacing ribs. Spacing ribs is dependent on the size of the boundary layer of the natural flow of the convector rib, spacing ribs should be such as to boundary layers should not be influenced. Passive chilled beam achieved too low performance due to their layout length, because optimization is made using mathematical simulations.

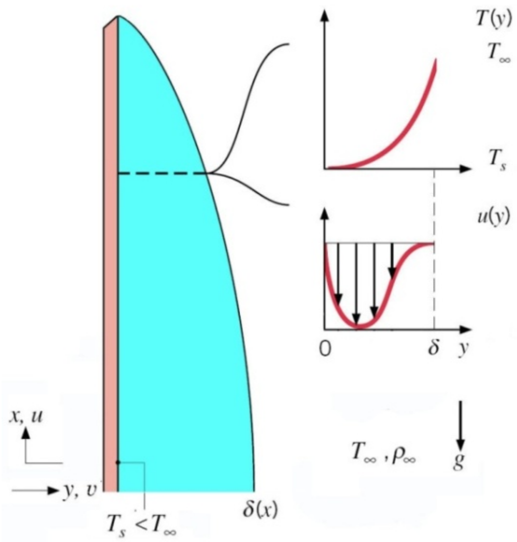

Fig.2. Velocity and temperature profile in the boundary layer of the vertical plate (rib).

II. INCREASING THE COOLING POWER OF PASSIVE CHILLED BEAM BY ADJUSTING ITS CONSTRUCTION

As a model passive chilled beam was selected four pipe passive chilled beam. On the basis of a mathematical model of passive chilled beam simulation program was created in Excel. In the simulation calculations were studied impacts, rib spacing, pipe diameter, height of the ribs, the cooling power, under constant input conditions, t_{11} = 16 °C, T = 7.5 K. All simulations were carried out by iteration to the required temperature gradient 16/19 °C.

Model of passive chilled beam:

a) Geometrics parameters: width, length, inner diameter of the pipe, the outside diameter of the pipe, the height of the ribs, the thickness of the ribs, spacing of the ribs,
b) Calculation of the required exchange surface heat exchanger: surface ribs and pipes.

Surface ribs and pipes.

The inner surface of pipe of the relevant section:

$$S_1' = \pi . d_1 . s_r \qquad [m^2] \qquad (1)$$

c) s_r – spacing of the ribs [m],
d_1 – inner diameter of the pipe [m],
d_2 – outside diameter of the pipe [m].

The entire inner surface of pipe:

$$S_1 = \frac{L_k . n_{rur}}{s_r} . S_1' \qquad [m^2] \qquad (2)$$

For the section all free pipes:

$$S_{rur} = \pi . d_2 . (s_r - \sigma_r) . n_{rur} . n_r \qquad [m^2], \qquad (3)$$

where
σ_r – thickness of the ribs [m],
n_{rur} – number of pipes [ks],
n_r – number of ribs [ks].

The outer surface of all ribs:

$$S_r = \left[B . h_r - \left(\frac{\pi . d_2^2}{4} . n_{rur} . 2 \right) \right] . n_r \qquad [m^2] \qquad (4)$$

B – width of the rib [m]

The entire external surface:

$$S_2 = S_r + S_{rur} \qquad [m^2] \qquad (5)$$

d) Selection of coolant: Interior temperature 26 °C, cooling water 16 °C,
e) A finding the physical properties of liquids: ρ, c, ν, λ.

A finding physical properties of fluids, changing the temperature, where appropriate, the function of the temperature.

f) Choice of flow rate in the heat exchanger: v_v.

The choice of the rate of flow of water to be set so as to achieve the desired thermal gradient 16/19 °C.

Water velocity in the pipes:

$$v_v = \frac{\dot{m}_v}{3600 . S_p . \rho} \qquad [m.s^{-1}], \qquad (6)$$

where
v_v – flow velocity in the pipe [$m.s^{-1}$],
S_p – flow cross section [m^2],
S_2 – size of the heat transfer surfaces of the heat exchanger [m^2].

g) Determination of heat transfer coefficient: α.

To determine the heat transfer coefficient on the side of the water is a factor dependent on the flow rate and temperature of the water. Is it possible to set according to the equation [2].

$$\alpha_i = 2900 . m_v . 0{,}99 . (1 + 0{,}014 . t_{11}) \qquad [W.m^{-2}.K^{-1}] \qquad (7)$$

To determine the heat transfer coefficient for passive chilled beam in the natural flow decides the size Prandtl and Grashof criteria, which is the result of Elenbaas semi-empirical correlation Nusselt numbers for isothermal parallel plates spaced sr [1] and is the size of the Rayleigh criteria-number:

$$Ra_{sr} = \frac{g . \beta . (T_{11} - T_{21}) . s_r^3}{\upsilon . a} . S_1' \qquad (8)$$

$$Nu_{sr} = \frac{1}{24} Ra_{sr} \left(\frac{s_r}{L} \right) \left\{ 1 - \exp \left[- \frac{35}{Ra_{sr} (s_r / L)} \right] \right\}^{3/4} \qquad (9)$$

Substituting we get the size of heat transfer coefficient on the rib:

$$Nu = \frac{\alpha_r . h_r}{\lambda} \Rightarrow \alpha_r = \frac{Nu . \lambda}{h_r} \qquad [W.m^{-2}.K^{-1}] \qquad (10)$$

where
hr – height ribs [m].

The heat transfer coefficient on the outside of the pipe, the following equation:

$$\alpha_e = \alpha_r . \psi \left[1 + (\eta - 1) . \frac{S_r}{S_2} \right] \qquad [W.m^{-2}.K^{-1}] \qquad (11)$$

Efficiency rib η:

Since the temperature of the surface of a finned pipe is not the same, an adjustment factor ψ and this has value for square ribs ψ = 0.85. Efficiency rib η [1].

h) Determined at middle logarithmic temperature difference:

Determined at middle logarithmic temperature difference based on the knowledge of the input and output temperatures of both substances.

$$\Delta t_{str} = \varsigma \frac{(t_{21} - t_{12}) - (t_{22} - t_{11})}{\ln \frac{t_{21} - t_{12}}{t_{22} - t_{11}}} \qquad [°C] \qquad (12)$$

t_{11} – inlet water temperature [°C],
t_{12} – outlet water temperature [°C],
t_{21} – temperature of the cooling air [°C],
t_{22} – air temperature cooled [°C],
Δt_{str} – the middle logarithmic temperature difference [°C].

Correction factor

$$\varsigma = \frac{\ln \frac{1 - P}{1 - RP}}{n . (1 - R) . \ln \left[1 + \frac{1}{R} . \ln \frac{R - 1}{R \left(\frac{1 - P}{1 - R.P} \right)^{\frac{1}{n}} - 1} \right]} \qquad (13)$$

$$P = \frac{t_{12} - t_{11}}{t_{21} - t_{11}} \qquad R = \frac{t_{12} - t_{22}}{t_{12} - t_{11}}$$

i) Calculation heat transfer coefficient: k.

Calculation of heat transfer coefficient based on the partial heat transfer coefficients.

Heat transfer coefficient:

$$k = \frac{1}{\frac{1}{\alpha_e} + \frac{S_2}{S_1} . \frac{1}{\alpha_i}} \qquad [W.m^{-2}.K^{-1}], \qquad (14)$$

where

S_1 – inner surface of pipe [m_2],
α_i – thermal conductivity inside the [$W.m^{-2}.K^{-1}$],
α_e – thermal conductivity to the outside of the [$W.m^{-2}.K^{-1}$],
k – the heat transfer coefficient [$W.m^{-2}.K^{-1}$].
j) Determination of heat flux: Q.

$$Q = k.S_2.\Delta t_{str} \quad [W] \qquad (15)$$

The aim of simulations calculation was to analyze the impact of structural parameters on cooling power passive chilled beam.

Passive cooling coil has the following design parameters:
d_1 – the outer pipe diameter 0.015 m,
s_r – 0.005 m spacing ribs,
h_r – rib height 0.06 m,
σ_r – rib thickness 0.00025 m,
L_k – passive ceiling heater length 1.8 m,
B – passive ceiling heater width 0.6 m,
n_{rur} – number of tubes 4.

The results of simulations to change the spacing ribs s_r

The simulations in changing the spacing of the ribs were constant all the design parameters (length, width, pipe diameter, rib height, rib thickness and number of tubes), only the spacing between the ribs was varied from 1 mm to 10 mm (Fig. 3).

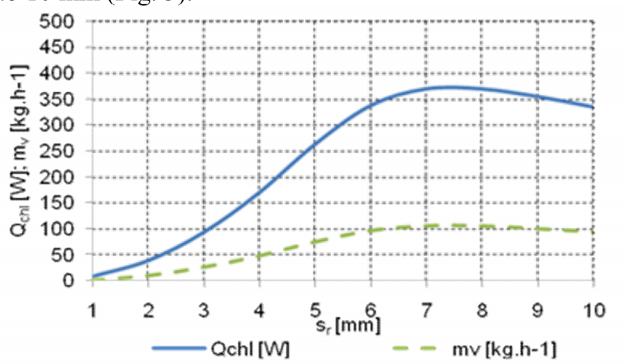

Fig.3. The results of simulations to change the spacing ribs s_r.

Change the space ribs from the original 5 mm to 8 mm will increase the power of 107 W, which is the maximum possible cooling power with the change of rib spacing.

Simulation results in changing the height of ribs h_r

In these simulations are constant parameters (length, width, pipe diameter, spacing of ribs, rib thickness and number of tubes), changed only the height of ribs from 10 mm to 100 mm (Fig. 4).

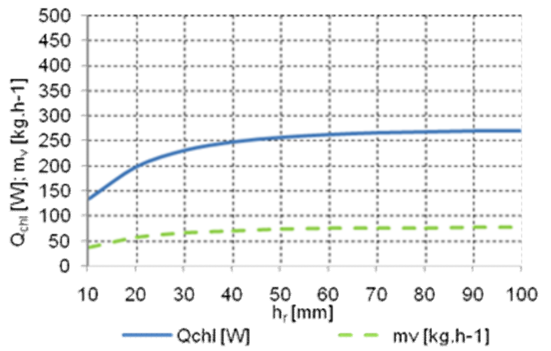

Fig.4. Simulation results in changing the height of ribs h_r.

Change the height ribs from 50 mm to 100 mm is achieved cooling power 269.89 W, which is the maximum possible cooling power to alter the height of rib. We also see that increasing the cooling power is the rib height 60 mm negligibly small. It shows us the optimum rib height for the cooling coil.

Results of the simulation by changing the spacing of the ribs at the height of the ribs with a given thickness of the rib

The simulation results (Fig. 5) are cooling power depending on passive chilled beam from rib space for different height of the ribs. Of dependence that the maximum cooling power depends on the rib space, but also the height of the rib. Depending on the height of the rib to move the maximum cooling power for example the rib height 50 mm have the maximum cooling capacity 320 W at 7 mm rib space, and the rib height 100 mm, the maximum cooling capacity 475 W at 8 mm rib space. This has to be respected in the construction of passive chilled beam.

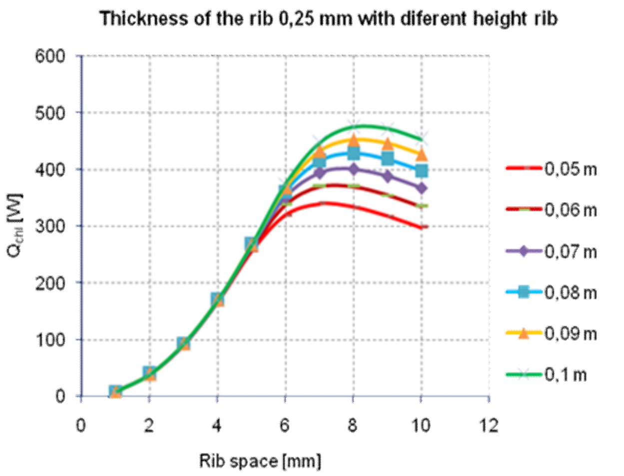

Fig.5. The resulting graph simulation power chilled beam PDK-F-600-Z-2000/160 depending on the thickness, spacing and height ribs.

Simulation results of changing the number of tubes

Based on the resulting parameters was performed further optimization, which investigated the influence number of tubes on the cooling power and the final weight convector.

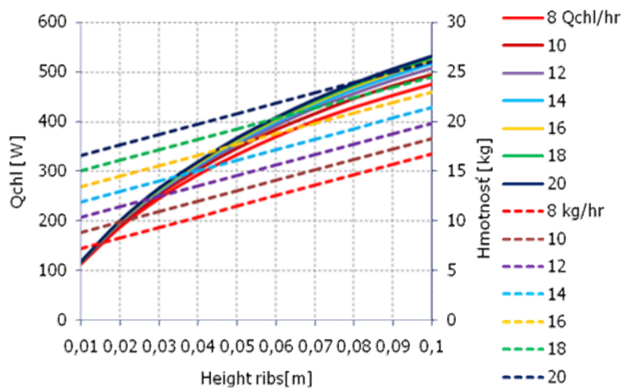

Fig.6. Power of chilled beam PDK-F depending on the number of tubes, the height of rib and its weight.

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With this change, to achieve maximum cooling power 532.58 W, with equipment weighing 26.08 kilograms already taking into account the previous optimization (Fig. 6).

The simulations showed that the cooling power to change the number of tubes increases, but the number of tubes 14 to 20, the effect of increasing the cooling power is negligible. This increase has an impact on weight, and hence the cost of production. Based on these simulations, it is recommended to implement passive chilled beam in the following design patterns:

– Optimal performance: 517.79 W,
– Number of tubes: 14 pcs,
– Rib height: 0.1 m,
– Rib length: 0.6 m,
– Pitch: 8 mm,
– Rib thickness: 0.3 mm,
– Weight: 21.41 kg.

III. Increasing the Cooling Power of Passive Chilled Beam With Change Temperature Gradient and the Change in Coolant Flow

The following cooling power depending on the flow of coolant can be seen as the device operates at a flow rate change (Fig. 7).

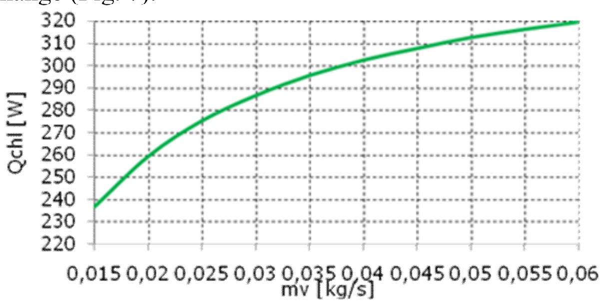

Fig.7. Dependence of changes flow on the cooling power (t_{11} = 16 °C, T_i = 25 °C).

Result of simulations, which compared the percentage change in cooling power with variations in the flow of temperature gradient and flow rate at which the investigated cooling power convector and the percentage change in cooling capacity based on maximum power at a flow rate 0.06 kg/s.

I. Percentage changes in the cooling power of variations in the flow rate based on 100 % power for ΔT = 7.5 K.

m_v [kg/s]	B-600-Lk-1800-4	
0.015	-24.73	-34.86
0.02	-13.80	-23.05
0.025	-7.32	-16.04
0.03	-3.04	-11.41
0.035	**0.00**	-8.13
0.04	2.27	-5.68
0.045	4.02	-3.78
0.05	5.42	-2.26
0.055	6.57	-1.03
0.06	7.52	**0.00**

IV. Model of the Boundary Layer for Rib Established Through Differential Equations Describing Natural Convection

Due to the optimization of spacing ribs passive chilled beam ceiling in relation to the boundary layer is necessary to establish the mathematical model. In developing the model is based on 2D flow, as shown in Fig. 2. It is based on the momentum equation (16), which is the same as for 2D between the layers and the volume expansion factors β.

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}-g+v\frac{\partial^2 u}{\partial y^2} \qquad (16)$$

If does not exist fluid movement in the direction y is the pressure gradient $\partial p/\partial y=0$. Therefore, the gradient $\partial p/\partial x$ must be the same in the boundary layer marginal layer on the outside. Assuming that the density varies linearly only with temperature and independent on pressure (this simplification, the literature says the Boussinesq approximation), momentum equation (16) then the resulting shape after treatment:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\beta(T-T_\infty)+v\frac{\partial^2 u}{\partial y^2} \qquad (17)$$

Introducing criterion similarities in equation (17) and the treatment we get the following criterion of similarity, called Grashof (18), which is a typical criterion for natural convection.

$$\frac{g\beta(T-T_\infty)L}{u^2}\cdot\underbrace{\frac{u^2L^2}{v^2}}_{Re^2}=\frac{g\beta(T-T_\infty)L^3}{v^2}\equiv Gr_L \qquad (18)$$

The characteristic dimension L is taken the amount of rib, where there is air movement. Equation for determining heat transfer coefficient is Nusselt criterion has the form

$$N_{UL}=f.(G_{rL}.P_r) \qquad (19)$$

$Gr_L.Pr$ is known as Rayleigh criterion. In natural convection are encountered with laminar or turbulent regimes. The criterion for determining the type of flow is the critical value of local Rayleigh criteria:

$$Ra_{x,krit}=Gr_{x,krit}.Pr=\frac{g\beta(T_w-T_\infty)x^3}{va}=10^9 \qquad (20)$$

For vertical surfaces is that if Ra_x > 109, the turbulent regime, where Ra_x < 109, the laminar regime. For a vertical wall, which in this case the vertical ribs passive chilled beam, using the equation for local heat transfer coefficient on the along plate:

$$\alpha_x=0.508Pr^{1/2}\frac{Gr_x^{1/4}}{(0.952+Pr)^{1/4}}\frac{\lambda}{x} \qquad (21)$$

and equation (22) to the boundary layer thickness:

$$\delta_x=4.3x\left[\frac{Pr+0.56}{Pr^2Gr_x}\right]^{1/4} \qquad (22)$$

where Gr_x is local Grashof number, which is taken as the characteristic dimension of the x-axis position on the board. The relation (21), it is clear that the heat transfer coefficient with increasing amounts of x decreases with $x^{1/4}$, while the boundary layer thickness increases with $x^{1/4}$. By integrating equation (21) of the walls dividing the amount of L obtained for the mean correlation coefficient of heat transfer, respectively. Nusselt numbers for laminar regime

$$\overline{Nu_L} = \frac{\overline{\alpha}L}{\lambda} = 0.678 Pr^{1/2} \frac{Gr_L^{1/4}}{(0.952+Pr)^{1/4}} \qquad (23)$$

V. Results Simulations

The cooling power of passive chilled beam has also considerable influence to spacing ribs. In relation to the boundary layer is necessary to choose a spacing of ribs, to avoid connection of the two layers in the limit space ribs. In the Fig. 8 is shown the dependence of boundary layer thickness and average factors heat transfer on the rib with wall temperature t_w = 16 °C at an ambient temperature $t_\infty = 25$ °C, which is in most cases the required temperature of chilled environment for measuring passive chilled beam. The results of simulations are indicated in Fig. 8, where it displays the behavior of velocity and temperature profiles of the boundary layers depending on the rib height. From these results, it is possible to determine the most appropriate structure to obtain optimal rib flow in the area of passive ribbed cooling convectors, and thus achieve maximum cooling performance passive chilled beam.

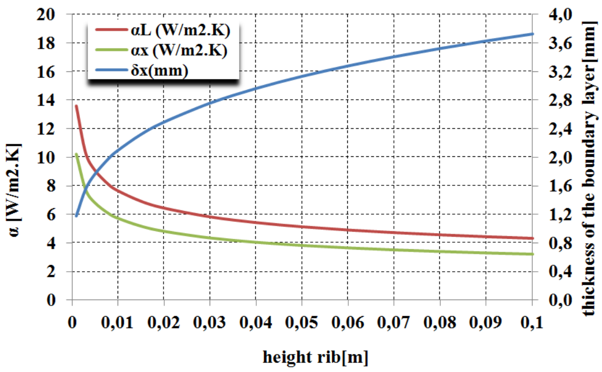

Fig.8. Dependence of boundary layer thickness and the average of heat transfer coefficient on the rib height.

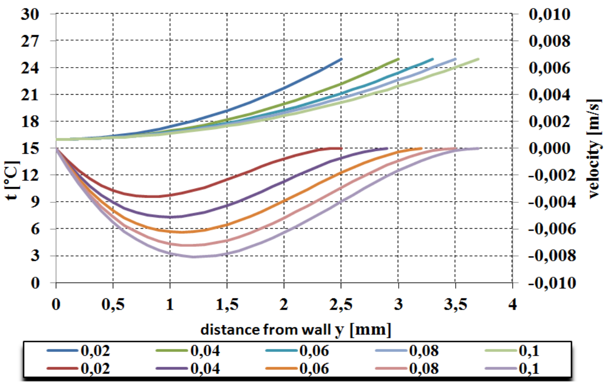

Fig.9. Dependence of rib height to velocity and temperature profile of the boundary layer.

When changing the input conditions, the behavior of velocity and temperature profiles change depending on the rib height. Fig. 10 and Fig. 11 present the predicted results of temperature and velocity profile of boundary layer for changing temperatures on the rib wall t_w = 18 °C. The above presented dependence shows that the temperature increase of the rib wall is resulting to reduced flow rates. For example, the rib of height 0.1 m increases the boundary layer thickness δx from 3.72 mm to 3.97 mm and thus may reduce the flow velocity 0.001 $m.s^{-1}$, resulting in a reduction of cooling performance.

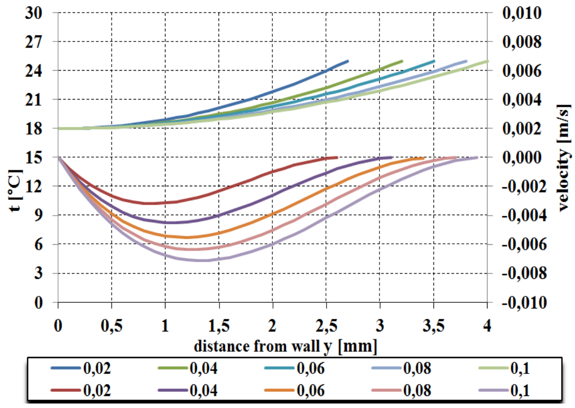

Fig.10. Dependence rib height to velocity and temperature profile of the boundary layer.

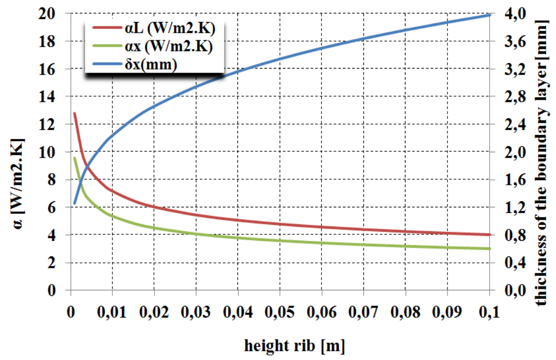

Fig.11. Dependence of boundary layer thickness and the average of heat transfer coefficient on the rib height.

For example, commonly used construction of passive convectors with the height rib of 0.06 m a rib spaced between the ribs 5 mm at the rib wall temperature t_w = 16 °C, the Fig. 8 shows that the boundary layer thickness is 3.27 mm. Similarly, it is also in the case of the rib wall temperature t_w at 18 °C, Fig. 11, which describes that the boundary layer thickness is 3.5 mm in both cases the conflict boundary layers. For the passive chilled beam appears in relation to the thickness of the boundary layer, as appropriate spacing ribs 6 to 7 mm. Without another consider influence on the effects cooling power convector of course.

VI. Conclusion

The results of mathematical simulations boundary layer in the intercostals space passive chilled beam that change spacing and rib height limit is affected by the layer, which affects the transport of heat from the cooling water to the environment, and thus the overall cooling power of passive chilled beam. The results of simulations can determine the optimal size and spacing of ribs up to maximize cooling performance through a passive chilled beam.

In simulations of cooling power depending on construction parameters (spacing ribs, rib height and thickness, diameter and number of tubes) in the temperature gradient 16/19 °C was found as the various construction parameters affecting the cooling power of passive chilled beam. The simulation results clearly show that by changing the spacing of the ribs to reach the biggest change of cooling power.

In the simulations, which compared the percentage change in the cooling power, depending on variations in the flow rates for a given temperature gradient was found in which the flow can be achieved by increasing the cooling power of the cooling convector. Similar dependence has been calculated and provided a constant flow of coolant when changing temperature gradient.

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