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THERMAL EFFICIENCY ESTIMATION OF THE PANEL TYPE RADIATORS WITH CFD ANALYSIS

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Abstract: There are many panel radiator manufacturers in Turkey. Their panel radiator designs are very similar and radiators that have been manufactured by various producers have very similar thermal efficiency values and specific heating per unit weight of the radiator. In this study, CFD analysis of existing panel radiators were made with a commercial CFD code of STAR-CCM+ with variable connection methods in three-dimensional space. Numerical thermal efficiency values were obtained and were compared with given catalogue values. Panel-convector-convector-panel, Type-22-600x500 steel panel radiator was used in this numerical study. In the content of this analysis, the effect of variation at air-side convective heat transfer coefficient on the thermal output was also investigated. After optimum air-side convective heat transfer coefficient had been determined, numerical analyses of the panel radiator were done based on this value. For top-bottom-opposite-end connection, mass flow rate distribution is greater than exact flow at first two and last three vertical ducts. In the middle of the vertical ducts towards inlet boundary, mass flow rate distribution corresponds to about zero. For top-bottom-same-end connection, mass flow rate distribution is greater than exact flow at first four vertical ducts. In the last part of the vertical ducts, mass flow rate distribution corresponds to about zero. Numerical results and commercial catalog values are very close each other for TBOE and TBSE connections, and thus two basic connection methods can be used for this panel radiator.

Keywords: Panel radiator, thermal efficiency, computational fluids dynamics, finite volume method

PANEL TİP RADYATÖRLERİN CFD ANALİZİ İLE TERMAL VERİM HESABI

Özet: Türkiye'de bir çok panel radyatör üreticisi bulunmaktadır. Panel radyatör tasarımları birbirlerine çok benzerdir ve değişik üreticiler tarafından üretilen radyatörler benzer termal verime ve benzer birim ağırlık başına özgül ısıya sahiptirler. Bu çalışmada, mevcut panel radyatörün CFD analizleri bir ticari CFD kodu olan STAR-CCM+ ile üç boyutlu olarak değişik bağlantı yöntemleri ile yapılmıştır. Sayısal termal verim değerleri elde edilip ve bilinen katalog değerleri ile karşılaştırılmıştır. Bu sayısal çalışmada, panel-kanat-kanat-panel, Tip-22-600x500 çelik panel radytör modeli kullanılmıştır. Bu çalışma kapsamında, hava tarafındaki ısı taşınım katsayısı değişiminin ısıl güç üzerindeki etkileri ayrıca incelenmiştir. Optimum hava tarafındaki ısı taşınım katsayısı belirlendikten sonra, sayısal çalışmalar bu değere gore yapılmıştır. Üstten girişi, çapraz tarafta alttan çıkışı olan bağlantı için, kütle debisi dağılımı ilk iki ve son üç dikey kanalda olması gereken akıştan daha fazla olduğu belirlenmiştir. Giriş sınırına yakın ortadaki dikey kanallarda, kütle debisi dağılımının nerdeyse sıfıra eşit olduğu görülmektedir. Üstten girişi, aynı tarafta alttan çıkışı olan bağlantı için, kütle debisi dağılımı ilk dört dikey kanalda olması gereken akıştan daha fazla olduğu belirlenmiştir. Geri kalan dikey kanallarda, kütle debisi dağılımının nerdeyse sıfıra eşit olduğu görülmektedir. Üstten girişi, çapraz tarafta alttan çıkışı olan bağlantı ve üstten girişi, aynı tarafta alttan çıkışı olan bağlantı için sayısal sonuçlar ve ticari katalog değerleri birbirine çok yakındır ve bu yüzden iki ana bağlantı yöntemi de bu panel radyatör için kullanılabileceği gösterilmiştir.

Anahtar Kelimeler: Panel radyatör, ısıl verim, hesaplamalı akışkanlar dinamiği, sonlu hacimler metodu

NOMENCLATURE

A	total area [mm^2]
c_p	specific heat [kj/kgK]
EN	European standard
H	panel radiator height [mm]
h_a	air heat transfer coefficient [W/m^2K]
h_i	enthalpy at inlet side [kj/kg]
h_o	enthalpy at outlet side [kj/kg]
k	thermal conductivity [W/mK]
L	module length of the radiator [mm]
$\dot{m}$	mass flow rate [m/s]

$\dot{Q}$	heat transfer rate [W]
$\dot{Q}_h$	heat transfer based on enthalpy [W]
$\dot{Q}_{tot}$	total heat transfer rate [W]
$Q^{'}$	heat transfer rate of one module [W]
Re	Reynolds number
TBOE	flow and return top and bottom at opposite ends
TBSE	flow and return top and bottom at the same end
TS	Turkish standard
T_i	temperature at inlet side [K]
T_o	temperature at outlet side [K]
V	fluid inlet velocity [m/s]

Greek Symbols

ΔT	temperature difference between inlet and outlet side [K]
μ	dynamic viscosity [Pa.s, kg/ms]
ρ	density [kg/m^3]

Subscripts

i	inlet condition
o	outlet condition

INTRODUCTION

Panel radiators are the most widely-used central-heating emitters to heat most homes and offices in Europe. There is a high demand for panel radiators due to their compact design and less place requirements. 80% of the heat output from radiators is natural convection, 20% of the heat output from radiators is radiation. Although radiators are known as radiator, most of their output is by natural convection [3]. Since panel radiators are elegant design, light, cheap and occupy less place, they are in common use at homes and offices. Radiators are the combination of water circulation channels and high convectors that is directly welded onto these panels. All panel radiators release a combination of radiant and convective heat into a room as hot water flows through them. Beyond this fundamental function is a virtually unlimited range of forms, sizes, colors, and artistic themes.

The aim of this research is that there are many panel radiator manufacturers in Turkey, but their panel radiator designs are very similar and due to this similar design, radiators that have been manufactured by various producers have very similar values of thermal efficiency and specific heating for unit weight of the radiator. In our research, CFD analysis of existing panel radiator will be made with a commercial CFD code of STAR-CCM+ with variable connection methods in three-dimensional space. Numerical thermal efficiency values will be obtained and will be compared with given catalogue values. There is insufficient 3-D numerical study about panel radiator in literature.

MATERIAL AND METHODS

The panel radiator has been drawn by means of CAD software according to original measurements of the PCCP (panel-convector-convector-panel) arrangement of the panel radiator. PCCP, Type-22 steel panel radiator is used in this numerical study. Heat output of the steel panel radiator has been measured according to EN 442 in an accredited laboratory [6]. Connection types of steel panel radiator are top-bottom-opposite-end, top-bottom-same-end. The outer panel is made of a shaped plate with horizontal and vertical depressions. In order to increase heating performance, some types of radiators are provided with a convector plate, welded to the vertical waterways of the panel. The panel is made of two stamped steel sheets welded together with a seam weld on the perimeter and with a spot weld where the depressions are. Since the panel radiator is symmetrical, a half of the geometry can be used for numerical study. A 500-mm-long, 600-mm-high and 105-mm-wide is the dimensions of the half of the panel radiator. A 150-mm-high, 473.5-mm-long is the dimensions of the convector. First four and last four convectors are smaller than middle ones to prevent the difficulties at the installation of T-Junctions. Panels and convectors are made of steel sheet. Water channels are 1.1 mm thick, the panel radiator has 25 mm pitch. The convectors are 0.5 mm thick, and have a height of 37 mm from the base. The width of one panel 12 mm, respectively.

Pre-processing

This numerical study is based on a domestic radiator which is in accordance with Standard TS EN442. Half of the geometry was used for numerical study because of the symmetrical structure of the panel radiator geometry, and then the drawn geometry was imported to STAR-CCM+.

Boundaries which belong to both fluid and solid were converted to interface and interfaces provide a connection between boundaries during the simulation setup and analysis process. Interface provides a contact interface for heat transfer between fluid-solid regions so. Interface allows mass and energy to be exchanged between fluid and solid regions. The surface remesher is used to re-triangulate an existing surface in order to improve the overall quality of the surface and optimize it for the volume mesh models. A prism layer mesh is composed of orthogonal prismatic cells that usually reside next to wall boundaries in the volume mesh. Tetrahedral meshes provide an efficient and simple solution for complex mesh generation problems. Mesh sizes of the panel radiator geometry are listed in Table 1.

The panel radiator with TBOE connection was meshed using tetrahedral volume meshing model and also surface remesher and prism layer mesher were selected. Figure 1 shows the mesh type and the mesh density of outer side of the panel radiator geometry. Figure 2 shows the mesh type and the mesh density of fluid flow part of the panel radiator.

Table 1. Mesh sizes of the panel radiator geometry

Number of Prism Layers	Number of Prism Layers	2
Prism Layer Stretching	Prism Layer Stretching	1.2
Prism Layer Thickness	Absolute Size	1 mm
Surface Curvature	# Pts/circle	36
Surface Size	Absolute Size	4 mm
Surface Size	Absolute Size	2 mm

Figure 1. Mesh density of outer side of the panel radiator with TBOE connection

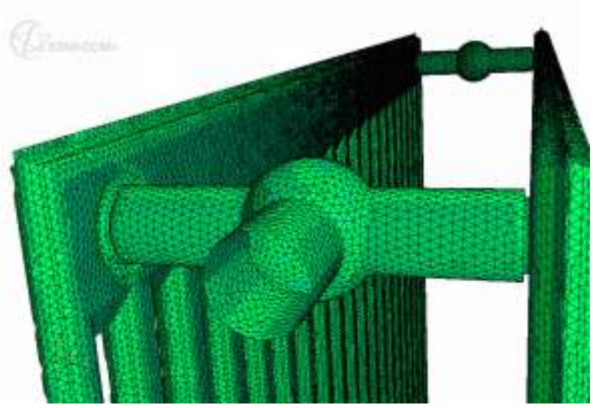

Figure 2. The mesh density of fluid flow part

At the end of the volume mesh, fluid region has 1,879,408 cells, 3,943,399 interior faces, 657,828 vertices, solid region has 2,917,488 cells, 4,920,090 interior faces, 928,657 vertices.

Processing

Steel panel radiator (AISI 316) used in this study was computed at inlet and outlet temperatures respectively, 75 ºC and 65 ºC according to EN 442 [9]. In the numerical study, inlet temperature and mass flow rate will be determined and outlet temperature will be measured according to boundary conditions. Inlet water temperature was specified as 75 ºC according to EN 442 [6].

In the analysis of panel radiator, we consider steady operation with no heat generation within the panel radiator, and we assume the thermal conductivity k of the material to remain constant. We also assume the air-side convection heat transfer coefficient to be constant and uniform over the entire surface of the panel radiator for convenience in the analysis.

TBOE panel radiator connection method was used to obtain the effects of different air-side heat transfer coefficients on the thermal output of the panel radiator. When inlet water temperature and mass flow rate were fixed, optimum air-side heat transfer coefficient was obtained and used for the other numerical analysis. Mass flow rate was computed from energy balance equation as given below.

$$\dot{Q} = \dot{m}\times c_p \times \Delta T \tag{1}$$

$$899 = \dot{m}\times 4189.8\times(75-65) \tag{2}$$

$$\dot{m} = 0.0214\ kg/s \tag{3}$$

All conditions and properties are defined via the STAR-CCM+ GUI. This study incorporates both multi-region and conjugate heat transfer. Outlet temperature was obtained according to the fixed inlet temperature and mass flow inlet. In this numerical study, rate of heat transfer of the panel radiator was obtained by the help of the forced convection model. Rate of heat transfer of the whole panel type radiator is 899 W/m.

Rate of heat transfer of the one module, which was calculated from the rate of heat transfer of the whole panel type radiator times the module length as follows.

$$Q^{'} = Q\times L \tag{4}$$

$$Q^{'} = 899\times 0.0017 \tag{5}$$

$$Q^{'} = 15.283\ W \tag{6}$$

Mass flow rate is found from the energy balance.

$$\dot{Q} = \dot{m}\times c_p \times \Delta T \tag{7}$$

$$15.283 = \dot{m}\times 4189.8\times(75-65) \tag{8}$$

$$\dot{m} = 0.00036\ kg/s \tag{9}$$

Under most practical conditions, the flow in a tube is laminar for Re<2300, fully turbulent for Re>10000, and transitional in between. But it should be kept in mind that in many cases the flow becomes fully turbulent for Re>4000 [4]. In order to define nature of the flow in a circular tube, Reynolds number was computed as follows.

$$\mathrm{Re} = \frac{4\times\dot{m}}{\pi\times D\times\mu} \tag{10}$$

$$\mathrm{Re} = \frac{4\times 0.00036}{3.14\times 0.017\times 0.0004} \tag{11}$$

$$\mathrm{Re} = 67.20 \tag{12}$$

which is less than the critical Reynolds number of 2300, and the flow regime of a circular tube is laminar.

Water was selected as liquid material. Material properties of water was computed as the average of inlet and outlet water temperatures. The tables of thermophysical properties of saturated water was used to compute material properties of water. Stainless steel (AISI 316) was selected for solid material. Material properties of stainless steel were determined according to the database of commercial CFD code of STAR-CCM+. Material properties of stainless steel (AISI 316) and water are listed in Table 2. Boundary conditions of the panel radiator geometry are also listed in Table 3.

Table 2. Material properties

	Water	Stainless Steel
Density (kg/m³)	977.7	8238
Dynamic Viscosity (Pa-s)	0.0004	
Specific Heat (J/kgK)	4189.8	468
Thermal Conductivity (W/mK)	0.6	13.4

Table 3. Boundary conditions of the panel radiator geometry

Boundary	Type	Physics Values	Inputs
Inlet	Mass Flow Inlet	Mass Flow Rate	0.0214kg/s
		Temperature	75 ºC
		Direction	x-direction
Outlet	Flow-Split Outlet	Split Ratio	1
		Direction	x-direction
Four T-Fittings	Wall	Thermal Specification	Adiabatic
Panel Surface	Wall	Thermal Specification	Convection
		Ambient Temperature	20 ºC
		Heat Transfer Coefficient	6.5 W/m²K
Convectors Surface	Wall	Thermal Specification	Convection
		Ambient Temperature	20 ºC
		Heat Transfer Coefficient	6.5 W/m²K

RESULTS

Effects of top bottom opposite end connection

The views of the scalar temperature distribution of fluid flow, convector and panel radiator at air side convective heat transfer coefficient of 6.5 W/m²K are given in Figure 3, 4, 5.

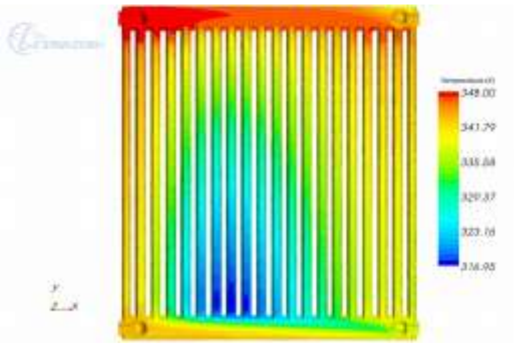

Figure 3. Scalar temperature distribution of fluid flow

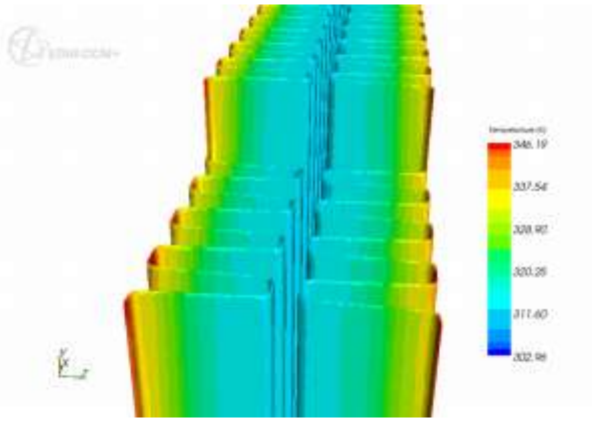

Figure 4. Scalar temperature distribution of convectors

Figure 3, 4 and 5 show that there are high temperature gradients are readily seen at the middle-bottom region of panel and fluid flow regions. This high temperature gradients are caused by distinct values of mass flow rates at vertical ducts.

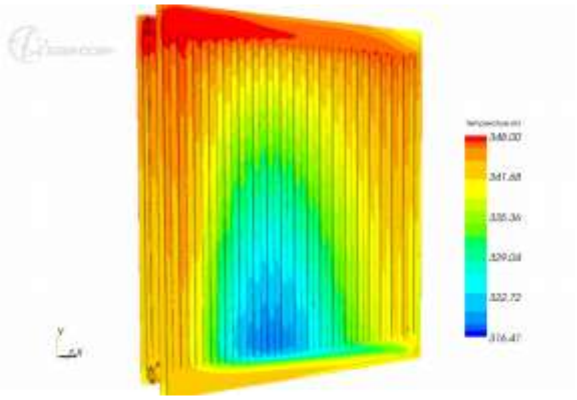

Figure 5. Scalar temperature distribution of the panel radiator

Plane section normal to the direction of z-axis was formed to show velocity magnitudes of fluid flow at vertical ducts at air-side convective heat transfer coefficient of 6.5 W/m²K is shown in Figure 6. Mass flow rate distribution through 20 vertical ducts is also given in Figure 7.

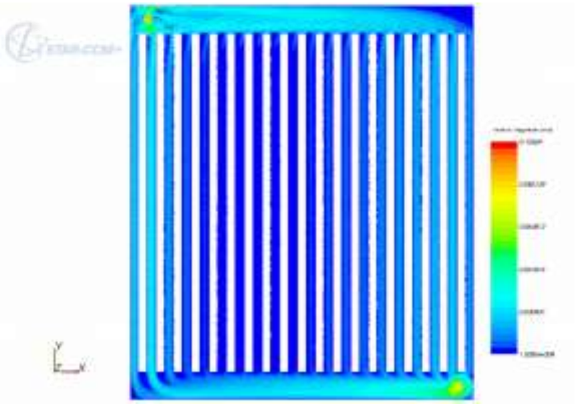

Figure 6. Velocity magnitudes of fluid flow at vertical ducts

In Figure 6, it can be seen that there is a non uniform mass flow rate distribution at vertical ducts. Water enters top distribution duct and predominant part of water moves into first two channels last three channels. First two and last three vertical ducts act like short circuit and water chooses to move into them than other ones. This yields the distinct mass flow rates along the vertical ducts of the panel radiator, and also yields the high temperature gradients at the middle bottom region of the panel raditor.

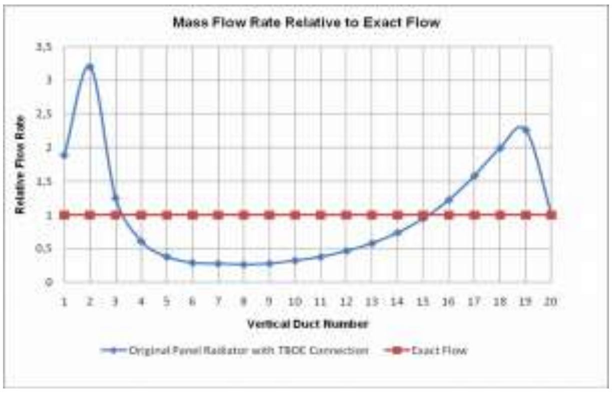

Figure 7. Mass flow rate distribution through all vertical ducts

In Figure 7, it can be seen that mass flow rate distribution is greater than exact flow at first two and last three vertical ducts. In the middle of the vertical ducts towards inlet boundary, mass flow rate distribution corresponds to about zero.

Evaluation of numerical result with experimantal result

Different air-side convective heat transfer coefficients were used to compute outlet water temperature of 65 °C that is related to panel radiator in accordance with TS EN442. Inlet water temperature of 75 °C is fix for all study. The numerical results of convective heat transfer coefficients of 5 W/m2K, 6.5 W/m2K, 8 W/m2K, 10 W/m2K were compared each other. Numerical results at different air-side heat transfer coefficients of the panel radiator with TBOE connection are listed in Table 4.

Table 4. Numerical results at different air-side heat transfer coefficients

Specifications	Symbol	Values			
Heat Transfer Coefficient (W/m^2K)	h	5	6.5	8	10
Mass Flow Inlet (kg/h)	$\dot{m}$	77.2	77.2	77.2	77.2
Inlet Water Temperature (°C)	T_1	75	75	75	75
Outlet Water Temperature (°C)	T_2	66.5	64.9	63.6	62
Room Temperature (°C)	T_r	20	20	20	20
Heat transfer rate (W) (Based on Enthalpy)	$\dot{Q}_h$	755	894.2	1015.8	1157.1
Heat transfer rate (W) (The Heat Output from the Radiator)	$\dot{Q}_{tot}$	753.7	892.1	1015.4	1156

Table 5. Numerical and catalog values at convective heat transfer coefficient 6.5 W/m²K

Specifications	Symbol	Numerical Results	Catalog Values	$\frac{Num.}{Exp.}$
Mass Flow Inlet (kg/h)	$\dot{m}$	77.2	77.2	
Inlet Water Temperature (°C)	T_1	75	75	
Outlet Water Temperature (°C)	T_2	64.9	65	0.998
Room Temperature (°C)	T_r	20	20	
Heat transfer rate (W) (Based on Enthalpy)	$\dot{Q}_h$	894.2	899	0.994
Heat transfer rate (W) (The Heat Output from the Radiator)	$\dot{Q}_{tot}$	892.1	899	0.992

Convective heat transfer coefficient of air-side is directly proportional to the thermal output of the radiator. Normally the larger air-side heat transfer coefficent, the higher the rate of heat transfer from the panel radiator. Table 4 should offer a good compromise between heat transfer rates of numerical study and experimental study, when the air-side heat transfer coefficent is 6.5 W/m2K. Therefore, the air-side heat transfer coefficent of 6.5 W/m2K was used in all numerical study.

The heat transferred to the air by means of forced convection model, which was calculated from the difference in enthalpy times the mass flow rate between the inlet and outlet of the water within the radiator as following.

$$\dot{Q}_h = \dot{m} \times (h_1 - h_2) \qquad (13)$$

$\dot{Q}_{tot}$ corresponds to heat transfer rate from panel and convector. When looking at the heat transferred from the radiator, the results are about the same as from the enthalpy calculations. For the fix inlet temperature of 75 °C, fix mass flow rate of 0.0107 kg/s and convective heat transfer coefficient of 6.5 W/m2K, outlet temperature of 64.9 °C was obtained. Numerical results compared with given catalog results which are in accordance with TS EN442 are listed in Table 5. In order to compare the discrepancies between the numerical result and catalog value, there is a ratio existing in Table 5 and this is shown as “Num./Exp.”.

Different ambient convective heat transfer coefficients were used to compute outlet water temperature of 65 °C and ambient convective heat transfer coefficient of 6.5 W/m²K was specified for numerical study. Mass flow rate is computed by means of Eq. 1 and used for numerical study. Commercial catalog values are in accordance with the standart TS EN442. 0.1% difference exists between numerical and catalog values for the outlet water temperature. Room temperature is 20 °C both numerical and commercial catalog of the panel radiator.

Rate of heat transfer of the panel radiator is computed by means of two ways. First one is that heat transfer rate is found by times of enthalpy difference between inlet and outlet and mass flow rate. Second one is that heat transfer rate is the sum of heat transfer rates from the panel and convector depending on STAR-CCM+. There is a very little difference between computed thermal output and commercial catalog values. 0.1% difference exists between heat transfer rate based on enthalpy and heat transfer rate based on catalog values. 0.8% difference exists between thermal output based on total heat transfer rate from the radiator and thermal output based on catalog values.

Effects of top bottom same end connection

The views of the scalar temperature distribution of fluid flow, panel radiator at air-side convective heat transfer coefficient of 6.5 W/m²K are given in Figure 8,9.

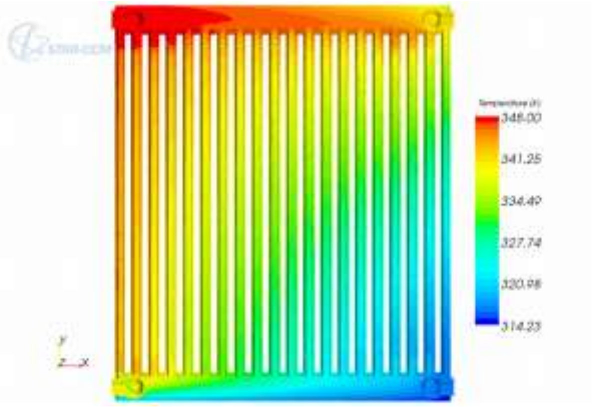

Figure 8. Scalar temperature distribution of fluid flow

Figure 8, 9 show that there are high temperature gradients are readily seen at the end-bottom region of panel and fluid flow regions. This high temperature gradients are caused by distinct values of mass flow rates at vertical ducts.

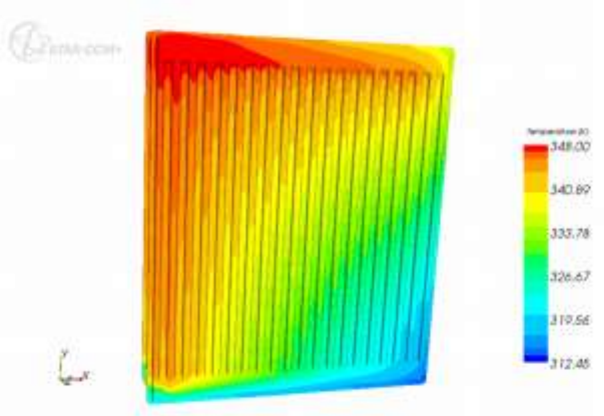

Figure 9. Scalar temperature distribution of the panel radiator

Plane section normal to the direction of z-axis was formed to show velocity magnitudes of fluid flow at vertical ducts at convective heat transfer coefficient of 6.5 W/m²K is shown in Figure 10. Mass flow rate distribution through 20 vertical ducts is shown in Figure 11.

In Figure 10, it can be seen that that supply water does not sluice complete radiator. Water does not reach to the last several vertical ducts and at this part velocity magnitude color bar shows zero. Predominant part of mass flow rate is immediately returned to bottom collecting duct at the beginning of the vertical ducts.

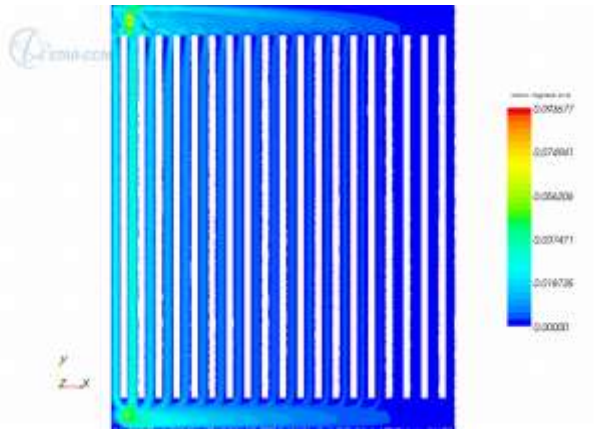

Figure 10. Velocity magnitudes of fluid flow at vertical ducts

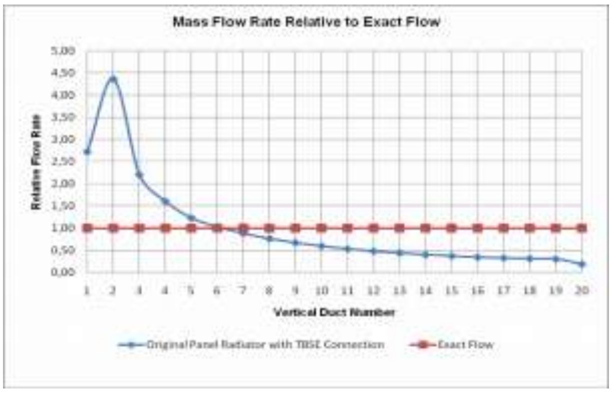

Figure 11. Mass flow rate distribution through all vertical ducts

First several vertical ducts act like short circuit. This yields the distinct mass flow rates along the vertical ducts of the panel radiator, and also yields the high temperature gradients at the end-bottom region of the panel raditor.

In Figure 11, it can be seen that mass flow rate distribution is greater than exact flow at first four vertical ducts. In the last part of the vertical ducts, mass flow rate distribution corresponds to about zero.

Evaluation of numerical result with experimantal result

The specifications of numerical results of original panel radiator with TBOE and TBSE connection are listed together in Table 6. In order to compare the discrepancies between the numerical results of TBOE and TBSE connections, there is a ratio existing in Table 6 and this is shown as “Num. TBOE/ Num. TBSE.”.

As explained before, the aim of this study, panel radiator connection were investigated to affects on rate of heat transfer of the panel radiator. 3.1% difference exists between thermal output based on enthalpy for top-bottom-opposite-end and top-bottom-same-end connections. 2.3% difference exists between thermal output based on total heat transfer rate from the radiator for top-bottom-opposite-end and top-bottom-same-end connections.

Table 6. Numerical results for top-bottom-opposite-end and top-bottom-same-end connections

Specifications	Symbol	Connection Method		$\frac{Num.TBOE}{Num.TBSE}$
		TBOE	TBSE	
Mass Flow Inlet (kg/h)	$\dot{m}$	77.2	77.2	
Inlet Water Temperature (°C)	T_1	75	75	
Outlet Water Temperature (°C)	T_2	64.9	65.2	0.478
Heat transfer rate (W) (Based on Enthalpy)	$\dot{Q}_h$	894.2	866.1	3.138
Heat transfer rate (W) (The Heat Output from the Radiator)	$\dot{Q}_{tot}$	892.1	871.6	2.297

Table 7. Numerical and catalog values at convective heat transfer coefficient 6.5 W/m²K

Specifications	Symbol	Numerical Results	Given Catalog Values	$\frac{Num.}{Exp.}$
Mass Flow Inlet (kg/h)	$\dot{m}$	77.2	77.2	
Inlet Water Temperature (°C)	T_1	75	75	
Outlet Water Temperature (°C)	T_2	65.2	65	1.003
Room Temperature (°C)	T_r	20	20	
Heat transfer rate (W) (Based on Enthalpy)	$\dot{Q}_h$	866.1	899	0.963
Heat transfer rate (W) (The Heat Output from the Radiator)	$\dot{Q}_{tot}$	871.6	899	0.969

For the fix inlet temperature of 75 °C, fix mass flow rate of 0.0107 kg/s and convective heat transfer coefficient of 6.5 W/m2K, outlet temperature of 65.2 °C was obtained. Numerical results compared with given catalog results which are in accordance with TS EN442 are listed in Table 7. In order to compare the discrepancies between the numerical result and catalog value, there is a ratio existing in Table 7 and this is shown as “Num./Exp.”

Mass flow rate is computed by means of Eq. 1 and used for numerical study. Given catalog values are in accordance with the standart TS EN442. 0.3% difference exists between numerical and catalog values for the outlet water temperature. Room temperature value is 20 °C for both results.

There is a little difference between computed heat transfer rate and commercial catalog values. 3.6% discrepancy exists between heat transfer rate based on enthalpy and heat transfer rate based on catalog values. 3% discrepancy exists between heat transfer rate based on total heat transfer rate from the panel radiator and heat transfer rate based on catalog values.

CONCLUSION

Type 22-600x500 panel radiator has been drawn by the help of CAD software according to dimensions of panel radiator manufacturer. Commercial catalog values of this panel radiator were compared with numerical results with respect to top-bottom-opposite-end and top-bottom-same-end connections type in the present paper.

The contact interface type is used to join together to permit conjugate heat transfer between a fulid and solid region. Thermal output of the panel radiator was specified by the help of a commercial CFD code of STAR-CCM+ withtop-bottom-opposite-end connection. In order to investigate the difference between thermal outputs of panel radiator with top-bottom-opposite-end and top-bottom-same-end connections, thermal outputs of panel radiator with top-bottom-same-end connection was also specified. Outlet water temperature of 65 °C was aimed to obtain according to fix inlet water temperature of 75 °C and fix mass flow inlet. Therefore, different ambient convective heat transfer coefficients were experienced. Outlet water temperature of 65 °C was obtained for the ambient convective heat transfer coefficient of 6.5 W/m²K. There is 0.1% difference between numerical result and commercial catalog value for thermal output based on enthalpy. There is 0.8% difference between numerical result and commercial catalog value for heat transfer rate based on total heat transfer rate from the radiator. Results should offer a good compromise between numerical and experimental studies for top-bottom-opposite-end connection.

Panel radiator with top-bottom-same-end connection was also investigated the effect of thermal output. Same methodology was used in panel radiator with top-bottom-same-end connection. 3.1% difference exists between thermal output based on enthalpy for top-bottom-opposite-end and top-bottom-same-end connections. 2.3% difference exists between thermal output based on total heat transfer rate from the radiator for top-bottom-opposite-end and top-bottom-same-end connections. There is 3.6% difference between numerical result and commercial catalog value for thermal output based on enthalpy. There is 3% difference between numerical result and commercial catalog value for thermal output based on total heat transfer rate from the radiator. Results should offer a good compromise between numerical and experimental studies for top-bottom- same-end connection. The difference between rate of heat transfer of the numerical and experimental studies is very small for engineering acceptance, and thus two basic connection methods can be both used for this panel radiator.

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