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Prediction of Heat Transfer Characteristicsof a Bottom Condesser Applied to Household Refrigerator

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Abstract: *The domestic refrigerator is no more a luxurious item but is an essential commodity. The performance of refrigeration system working on vapor compression cycle is depends on condenser performance. The hot-wall heat exchanger is widely used as a condenser in household refrigerator. In modern refrigerator the bottom condenser is used as a part of condenser. The main purpose is toevaporates the drain waterand also used to desuperheat refrigerant before condensation. The research paper presents the heat transfer characterstics in bottom condenser with help of numerical simulation.The mathematical model is used to carry out the energy analysis of bottom condenser. The numerical simulation of bottom condenser is carried out, first with air as cooling medium and second, water as cooling medium. The result of numerical and analytical analysis of bottom condenser shows that 28-30% more heat is absorbed by the water in bottom condenser which is much higher as compared to air as a cooling medium. The average heat transfer rate in bottom condenser with air is 2.0411W and with water is 145.2W. This results in this paper leads to optimization of heat transfer in hot wall condenser. The heat duty of the hot wall condenser decrease leads to decrease in heat infiltration load to refrigerant compartment.*

Keywords: *Refrigerator, Condenser, VCR system, R-600a, CFD analysis.*

NOMENCLATURE

Q_{model}	Heat transfer rate [W]
U_i	Refrigerant Side Or Tube Inside Overall Heat Transfer Coefficient [W/m^{2}K]
A_i	Heat transfer area [m^2]
T_{ref}	Refrigerant inlet [°c]
T_c	Cooling fluid temperature [°c]
T_s	Outer surface temperature of the tube [°c]
L	Tube length [m]
d_i	Inside diameter of the tube [m]
d_o	Outside diameter of the tube [m]
h_{ref}	Refrigerant Side Heat Transfer Coefficient [W/m^{2}K]
h_C	Cooling Fluid Side Heat Transfer Coefficient [W/m^{2}K]
K_t	Thermal conductivity of tube[W/mK]
Nu_c	Nusselt number of cooling fluid
Ra_c	Rayleigh number of cooling fluid
Gr_c	Grashoff number of cooling fluid
Pr_c	Prandtl number of cooling fluid
β_c	Thermal expansion coefficient of cooling fluid[1/K]
L_{ch}	Characteristic length for tube [m]
K_c	Thermal conductivity of cooling fluid[W/mK]
Re	Reynold number
Nu_{ref}	Nusselt number of refrigerant
Re_{ref}	Reynold number of refrigerant
Pr_{ref}	Prandtl number of refrigerant
m_{ref}	Mass flow rate of refrigerant[kg/sec]
μ_{ref}	Dynamic viscosity of refrigerant[ns/m^2]
Cp_{ref}	Specific heat of refrigerant[j/kgk]
K_{ref}	Thermal conductivity of refrigerant[w/mk]

I. Introduction

In developing countries, the demand of energy is continuously increasing due to increase in use of energy-intensive products. In the residential buildings, the use of energy-intensive product also contribute to the greenhouse gas emissions which shows adverse effect like global warming, depletion of ozone layer etc. Energy saving methods can be adopted by the users to partly reduce the household energy consumption and associated emission[1]. As this refrigerator is common everywhere and which requires continuous power supply so it consumes about 15% of the worldwide energy [2, 3]. To enhance the energy efficiency and the performance of the domestic refrigerator, several approaches areused such as use of alternative refrigerants and optimization of refrigeration system components. The replacement of refrigerant may not give good performance improvement of domestic refrigerator system since the power consumtion of refrigerator is close or slightly higher with alternate refrigerants instead of conventional ones[4]. Therefore, suitable modification of system component may improve the performance of domestic refrigerator. Domestic refrigerators consist of four main components: compressor, condenser, evaporator and expansion device. The energy consumption of domestic refrigerator is also depends on the condenser because it reported that total energy consumption decreased by 2 % if the condenser temperature reduced by 1^0C. [5]. The aesthetics point of view and to avoid leakge during transportation, manufactures replaced the wire tube condensers by hot-wall condensers in new refrigerators.[6] In recent years, the bottom condenser has begun to be used before hot-wall condenser to evaporate the drain water continuously in a domestic refrigerator. In the Asian countries, air cooled skin condensers (also known as hot-wall condensers). Elias and Rodolfo have evaluated the heat transfer rate through a numerical and experimental study on skin condensers. It is observed that the 68% of heat is transferred to the atmosphere through walls and 32% of heat is transferred to the refrigerated compartment, which increases the compressor load in refrigeration system [7]. M. Hosoz et al. has presented experimentally that the water-cooled condenser shows higher performance than air cooled condenser in terms of cooling capacity, condenser duty and the coefficient of performance under the same operating temperatures. Hence to improve the performance of refrigerator , research should be carried out to replace the air cooled condenser by water-cooled condenser [8].In recent years, the bottom condenser has been used as a part of hot-wall condenser to evaporate the drain water continuously in a domestic refrigerator. TheThe pictorial view bottom condenser used in refrigerator is shown in figure 1,the technical specifications are represented in table 1, which consists of a bundle of aluminium tubes with plastic box. Apart from the increase in heat transfer rate, the material consumption in terms of tube length required in the hot-wall condenser is reduced with help of bottom condenser.

Fig. 1 Refrigerator with bottom condenser

Table 1: Technical details of a Bottom condenser

Parameter	Specifications
Refrigerator capacity	284 litre
Condenser heat duty	450-500 Watts
Condenser tube material	Copper
Condenser box dimensions	230 X 210X 65mm
Tube outer diameter (OD)	5.2 mm
Tube Innner diameter (ID)	4.0 mm
Total tube length	4800 mm

In this paper, the heat transfer behavior and temperature distribution is presented with help of numerical simulation. The performance of bottom condenser of the domestic refrigerator with water and air as a cooling medium has been studied. As the water added to bottom condenser extract the heat from high-temperature refrigerant and which leads to improving the performance of domestic refrigerator .

II. Heat Transfer Analysis Of Bottom Condenser

The two dimentional model of bootomcondenser is as shown in Fig. 2.Desuperheating zone occupies a relatively small portion of the condenser, due to the large temperature deferential between superheated refrigerant vapour and ambient air. In this zone refrigerant vapour is cooled to refrigerant condensing temperature corresponding to condenser pressure. The non-dimensional heat transfer parameter describing these phenomena, Nusselt number, is related to the non-dimensional Reynolds and Prandtl numbers in the following form .

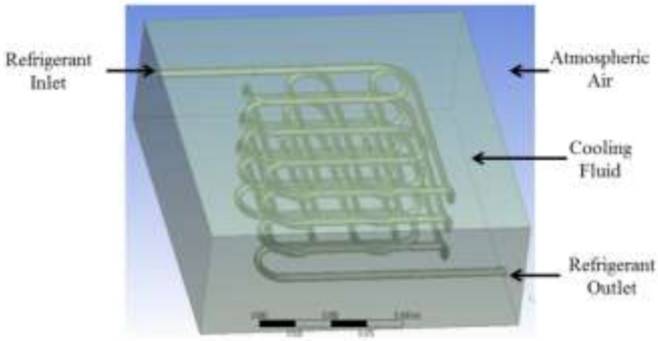

Fig. 2 Model of bottom condenser for analysis

Assumption:
1. Natural convection heat transfer is considered only.
2. There is no recirculation of cooling fluid due to walls of a box of the bottom condenser.
3. The initial temperature of cooling fluid and atmospheric air is 25^0C.
4. The properties of refrigerant are considered at saturation condenser temperature i.e. 43^0C.
5. The inlet temperature of the refrigerant is considered is 60^0C.
6. The initial tube temperature is considered is 60^0C.

The analytical model developed by Kara and Guraras [9] is used for the heat transfer analysis of a bottom condenser . The heat transfer analysis is carried with an elemental unit in control volume that consists of a tube and cooling medium.The heat transfer rate from the elemental model is computed first and results are integrated for whole bottom condenser to get net heat transfer. Fig. 3 shows the cross-section of the elemental portion and electrical analogy for bottom condenser which is considered for analysis.

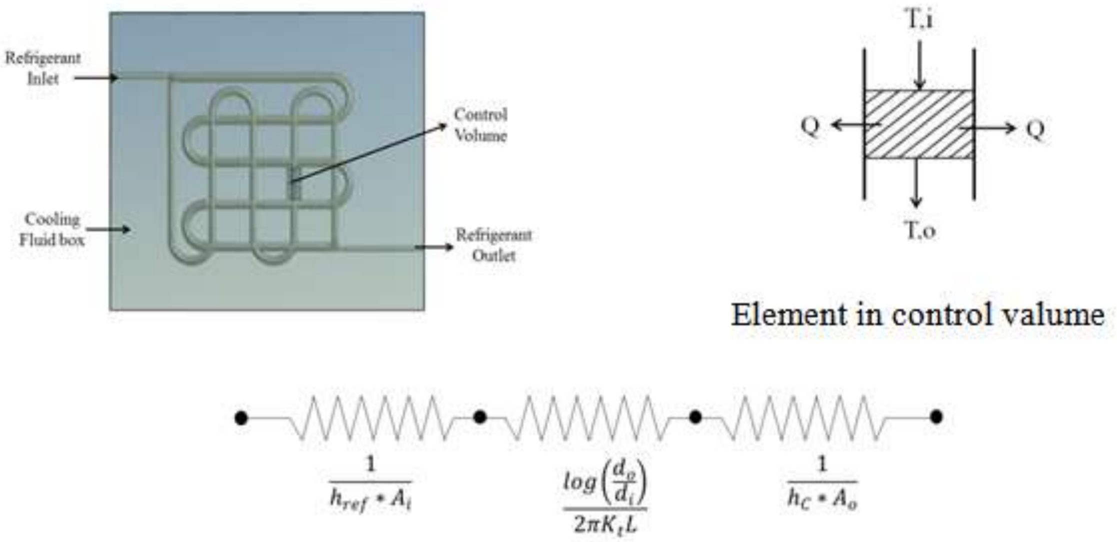

Fig.3: Cross section of element and eletrical analogy in the bottom condenser

2.1 Heat transfer rate

In bottom condenser the refrigerant flows inside the tube and cooling fluid is filled outside the tube in the tray. The heat flux rate and heat transfer rate between the refrigerant ,cooling fluid and tube surface is determine by using equation 1 and 2.

$Q_{model} = U_i A_i (T_{ref} - T_c)(W)$(1)

$$\frac{Q_{model}}{A_i} = U_i (T_{ref} - T_c) \left(\frac{W}{m^2}\right) \quad (2)$$

2.2 Heat transfer area (A)

The refrigerant side or tube inside heat transfer area of the bottom condenser is calculated by using equation 3.

$$A_i = \pi d_i L \;\; (m^2) \quad (3)$$

2.3 Overall heat transfer coefficient

The refrigerant side or tube inside overall heat transfer coefficient $U_i$depends on the tube inside diameter, tube outside diameter, refrigerant side convective coefficient, cooling fluid side convective coefficient and tube material, which is given by (Kara &Güraras, 2004).

$$U_i = \frac{1}{\frac{1}{h_{ref}} + \frac{d_i * log\left(\frac{d_o}{d_i}\right)}{2K_t} + \frac{d_i}{h_C * d_o}} \quad (4)$$

2.4 Outside heat transfer coefficient of tube

The heat transfer coefficient on the outer surface of the tube or cooling fluid side in single-phase flow is given by (Fand, 1977):

$$Nu_c = 0.474 Ra_c^{0.25} Pr_c^{0.047} \quad (5)$$

$$Ra_c = Gr_c * Pr_c \quad (6)$$

$$Gr_c = \frac{g\beta_c (T_s - T_c) {L_{ch}}^3}{{v_c}^2} \quad (7)$$

$$\beta_c = \frac{1}{T_m} = \frac{2}{T_s + T_c} \quad (8)$$

$$Pr_c = \frac{\mu_c * Cp_c}{K_c} \quad (9)$$

Where, the characteristic length,L_{ch} for a horizontal tube is equivalent to the outer diameter ($L_{ch} = d_o$). The outer heat transfer coefficient of tubeis related to the Nusselt number as,

$$h_C = \frac{Nu_c * K_c}{L_{ch}} \quad (10)$$

2.5 Inner Heat Transfer Coefficient of tube

In the single-phase region, the heat transfer coefficient on refrigerant side is computed from the following correlation (Traviss, 1972),

In laminar region (Re>2100)

$$Nu_{ref} = 1.86 {Re_{ref}}^{0.33} {Pr_{ref}}^{0.33} \left(\frac{d_i}{L}\right) \left(\frac{\mu_{b,ref}}{\mu_{w,ref}}\right)^{0.5} \quad (11)$$

In turbulent region (Re > 10,000)

$$Nu_{ref} = 0.023 {Re_{ref}}^{0.8} {Pr_{ref}}^{0.33} \left(\frac{d_i}{L}\right) \left(\frac{\mu_{b,ref}}{\mu_{w,ref}}\right)^{0.14} \quad (12)$$

The above equation can be used in common form for cooling fluids with Prandtl number in the approximate range in 0.7-100 and tubes with L/d_i> 60 is

$$Nu_{ref} = 0.023 {Re_{ref}}^{0.8} {Pr_{ref}}^{0.3} \quad (13)$$

Where

$$Re_{ref} = \frac{4 m_{ref}}{\mu_{ref} * di} \quad (14)$$

$$Pr_{ref} = \frac{\mu_{ref} * Cp_{ref}}{K_{ref}} \quad (15)$$

The inner heat transfer coefficient of the tube is related to the Nusselt number as,

$$h_{ref} = \frac{Nu_{ref} * K_{ref}}{d_i} \quad (16)$$

The following Table 2 shows the Nusselt Number and convective heat transfer parameters for both the cooling fluids obtained from analytical energy analysis:

Table 2.Nusselt Number and convective heat transfer parameters for air & water

Parameters	Air	Water	Unit
The nusselt number for cooling fluid (Nu_c)	2.24	16.64	-
heat transfer coefficient of cooling fluid (h_c)	10.45	1921.11	W/m^2K
The overall heat transfer coefficient of the tube (Ui)	13.26	612.74	W/m^2K
Heat Flux on the inner surface of the tube (Q/Ai)	464.1	21446.1	W/m^2
Heat transfer (Q)	27.99	1293.59	W

III. Numerical Analysis

The numerical simulation of condenser model is carried out using ANSYS software. The bottom condenser model and meshing is as shown in Fig. 4 and 5 respectively. In present work, the transient natural convection numerical simulation has been done for the bottom condenser of the refrigerator. Air & water is used alternatively as a cooling medium for condensation. The transient simulation is done for 30 minutes for both cooling fluids. The first simulation is carried out with air as a cooling fluid in the condenser, subsequently with water as cooling fluid. The meshed model of the bottom condenser is shown in the following figures.

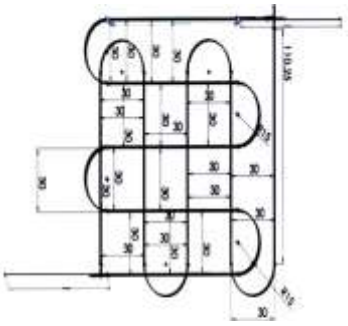

Fig.4 Sketch of the condenser tube

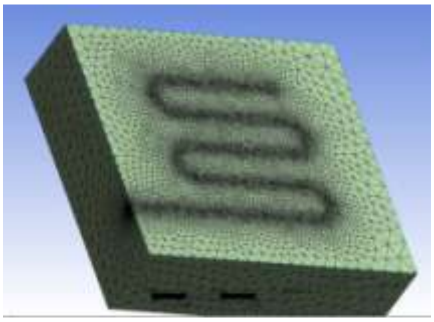

Fig. 5 Meshing of Bottom condenser

Quality of the geometry is what matters at the end so it is checked at the end of the procedure. It is checked by using 'Skewness' from mesh tab as shown in the following table,

Table 3: meshing model details of the Bottom condenser

Parameter		Specifications
Statistics		
1.	Nodes	1678900
2.	Elements	6254433
Mesh Metric		
1.	Minimum	7.4251E-07
2.	Maximum	0.8991
3.	Average	0.2288
4.	Standard Deviation	0.1207

IV. Result And Discussion

The results of variation of various parameters for both types of cooling fluid are shown below,temperature variation of refrigerant domain is shown in figure 6 and figure 7

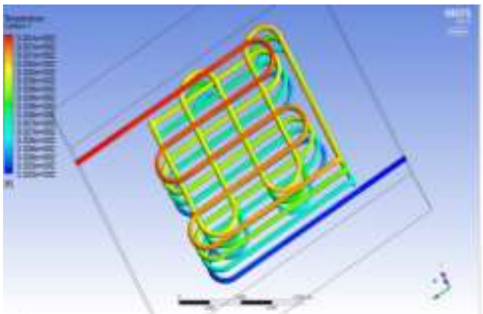

Fig.6 Temperature variation of Refrigerant Domain For Air cooled condenser

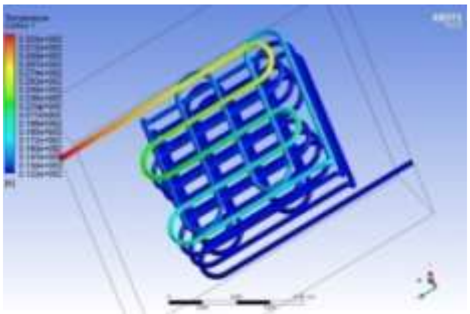

Fig.7 Temperature variation of Refrigerant Domain for Water-cooled condenser

The figure shows for same inlet temperature (333k) & pressure, bottom condenser with water shows 312 k outlet temperature of refrigerant & for bottom condenser with air is 332k. The temperature drop inair cooled condenser is much less than the water cooled condenser because of water heat transfer properties.Variation of Temperature distribution of cooling medium domain near contact between tube &cooling fluid.

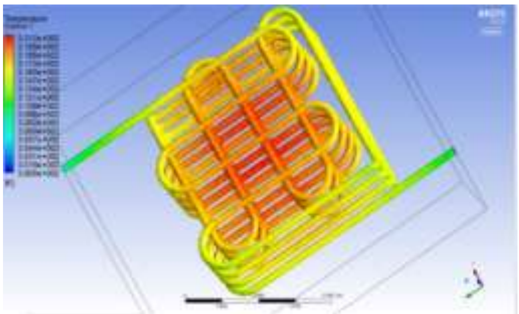

Fig. 8 Temperature distribution of cooling fluid domain near contact between tube &cooling fluid for Air cooled condense

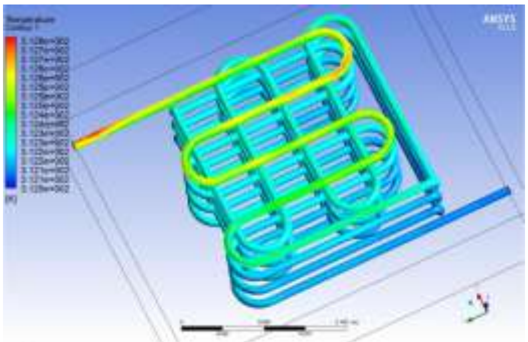

Fig. 9 Temperature distribution of cooling fluid domain near contact between tube &cooling fluid for Water cooled condenser

From the figure 8 and figure 9, air-cooled condenser shows non-uniform temperature distribution of air on the contact region between tube & air, where as water-cooled condenser shows uniform temperature in the same region.

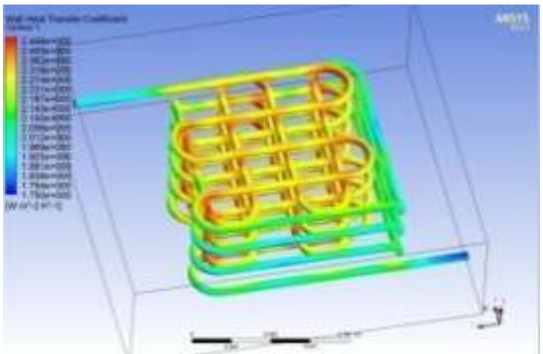

Fig. 10 The variation of Convective heat transfer coefficient of cooling fluid on tube wall for Air cooled condenser

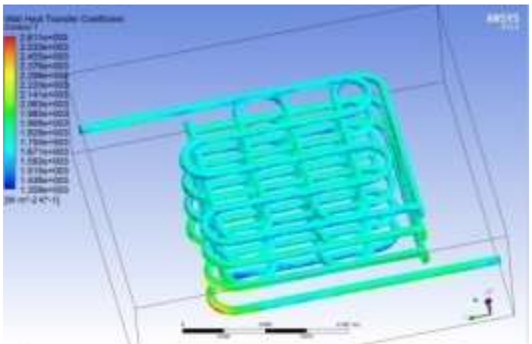

Fig.11 The variation of Convective heat transfer coefficient of cooling fluid on tube wall for a water-cooled condenser

Variation of convective heat transfer coefficient of cooling fluid on the tubesurface is shown in figure 10 and figure 11. The results shows that the higher convective heat transfer coefficient is observed for water as compared to air on the tube- cooling fluid contact region.

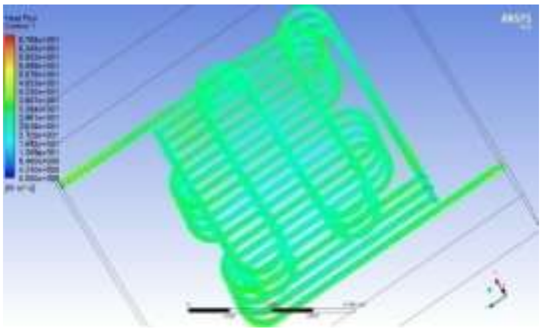

Fig. 12 The variation of heat flux on the inner surface of the tube for Air cooled condenser

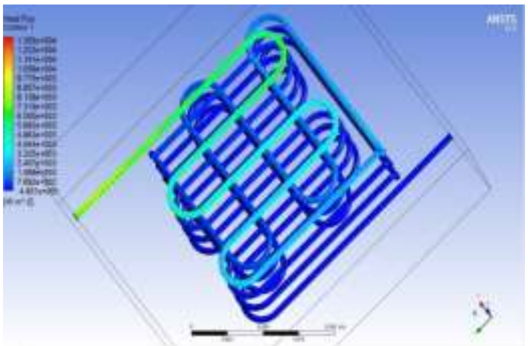

Fig. 13 The variation of heat flux on the inner surface of the tube for a water-cooled condenser

Variation of heat flux on the inner surface of the tube is presented in Fig. 12 and Fig.13. The result shows that the higher heat flux for water-cooled condenser is observed as compared to air cooled condenser on the tube- cooling fluid contact region because of higher convective heat transfer coefficient for water. Average heat Flux on the inner surface of the tube 33.84 W/$m^2$and with water is 2407.2 W/m^2 and average heat transfer 2.0411W with air and 145.2 W with water.

V. Conclusions

The main purpose of the present work is to reduce the energy consumption of refrigerator system with HC600a as a refrigerant by using water as cooling fluid in bottom condenser rather than air. The paper investigates the effect of surrounding cooling medium on the bottom condenser capacity to reject the heat.A significant improvement in system performance and reduction in energy consumption of a refrigerator is observed with water cooled bottom condenser. Following conclusions are drawn based on numerical analysis.

1. The average heat transfer rate in bottom condenser with air is 2.0411W and with water is 145.2W.
2. The domestic refrigerator of capacity 284 litres has near about 400W heat duty in the condenser. 28% heat absorbed by water in the bottom condenser and 72% heat rejected by air in hot-wall condenser.
3. The heat duty of the hot wall condenser decrease by 28% leads to decrease in size of hot wall condenser and decrease in amount of heat infiltration to refrigerant compartment.
4. To maintain the better performance of water-cooled bottom condenser make-up water is added periodically in bottom condenser is an increase in power saving as compared to the air cooled bottom condenser.

Conflict of interest The authors declare that there is no conflict of interests regarding the publication of this paper.

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