NUMERICAL INVESTIGATION OF AN EVACUATED TUBE SOLAR COLLECTOR IN A SOLAR ASSISTED ROOFTOP UNIT

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Abstract. In this study, numerical analysis of an evacuated tube solar collector integrated into the discharge line in a rooftop air conditioner is carried out. The goal in this system is to increase the efficiency of the unit by reducing the compressor energy consumption with the solar collector. The solar collector consists of vacuum tube collectors. Inside the vacuum tube, there is a copper pipe installation through which the R410a refrigerant in the superheated vapor phase, which is compressed by the compressor, passes. The remaining volume from the copper pipes in the tube is filled with a heat transfer fluid to increase the collector efficiency. In this study, the type of heat transfer fluid filled to the collector for the operating condition of the unit in summer and winter conditions are investigated parametrically and numerically. With the findings obtained, the surface temperature of the copper pipe installation in the collector in the compressor discharge line, depending on the type of heat transfer fluid, is presented comparatively.

Keywords. HVAC & R, solar energy, energy efficiency, computational fluid dynamics
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1. Introduction

Today, energy efficiency in HVAC&R systems has become an important issue on a global scale. Among these systems, one of the most widely used devices globally is rooftop air conditioning units. Rooftop air conditioners are a familiar technology but integrating renewable energy sources such as solar energy into the refrigeration cycle is an innovative approach. In the literature studies, two types of such an integration stand out; (i) to meet the fan and compressor power consumption of photovoltaic systems and rooftop air conditioning unit, (ii) to use solar thermal energy as an evaporator in the refrigeration cycle of the refrigerant, as well as to use the solar thermal energy to obtain hot water/air. For the second use method, the placement of the collector before the compressor has been widely studied in the studies conducted in the literature. The purpose of this increasing the evaporation temperature to provide energy efficiency. Torres-Reyes et al. (1998) [1] and (2001) [2], Cervantes et al. (2002) [3] reported that they worked both theoretically and experimentally on a solar assisted heat pump with the direct expansion of the refrigerant in the solar collector and performed a thermodynamic optimization. Chaturvedi et al. (1991) [4] and (1998) [5], Aziz et al. (1999) [6] are carried out on the thermodynamic analysis of two-component, two-phase flow in solar collectors with the application of a direct expansion solar assisted heat pump. Their results show that changes in mass flow rate and absorbed solar heat flux have significant effects on collector tube length and refrigerant heat transfer coefficient. It is observed that changes in tube inlet diameter and collector pressure has a negligible effect on the collector size but had a significant effect on the heat transfer coefficient. The increase in the quality of the refrigerant mixture is observed to be gradual along the main length of the pipe with a rapid rise near the end of the pipe. Apart from these studies, the use of evacuated tube solar collector with direct expansion after the compressor is quite new.

In this study, numerical parametric analyses are carried out on an evacuated tube solar collector integrated into the compressor discharge line, unlike the literature. By filling the different heat transfer fluids in the market into the vacuum tubes, the efficiency of the collector is examined, and the most suitable heat transfer fluid is determined.

2. MATERIAL AND METHOD

2.1 Model and Mesh

The model of the evacuated tube of the solar collector examined in this study and model is shown in Figure-1. Here, Fig. 1(a) is the top view of the evacuated tube, and Fig. 1(b) is the isometric view. The evacuated tube structure, which is numerically analysed, is in the standard dimensions and has an outer diameter of 53 mm and an inner diameter of 43.8 mm. The inner volume of the tubes is 2.6 liters. Its total length is 1800 mm. The tube consists of two concentric cylindrical glass structures. There is a vacuum gap between these two-cylinder structures. This space provides insulation to store the heat absorbed from the sun in the interior.

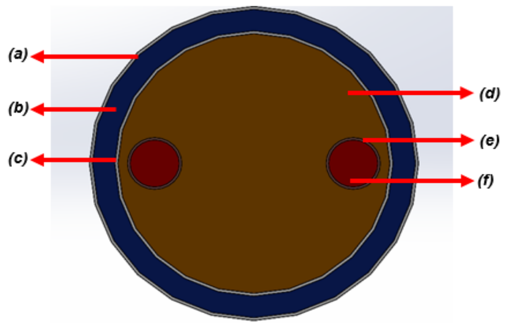

Fig. 1 (a) – Numerical Model, (a) evacuated tube outer glass zone, (b) vacuum zone (c) evacuated tube inner glass zone, (d) heat transfer fluid zone (e) copper tube zone (f) refrigerant zone.

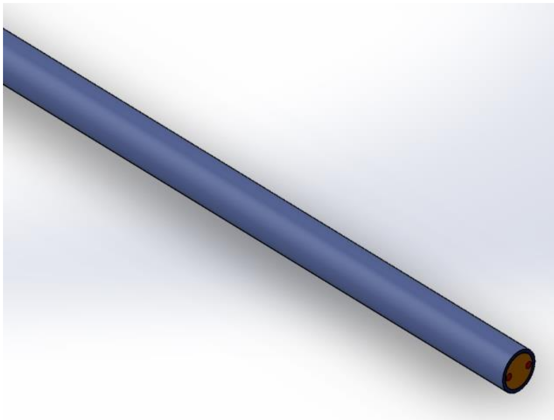

Fig. 1 (b) – Isometric View

In the numerical model, there is a u-shaped copper piping installation inside the vacuum tubes. The diameter of the copper tube is 3/8" (9.595 mm). The refrigerant compressed by the compressor enters the collector from the left side and leaves the collector from the right side in Fig. 1 (a). The goal here is to improve the heat transfer mechanism of the energy taken from the solar radiation to the refrigerant circulating in the copper pipe installation by using the heat transfer fluid and to increase the collector efficiency. The mesh structure of the numerical model is shown in Fig. 2.

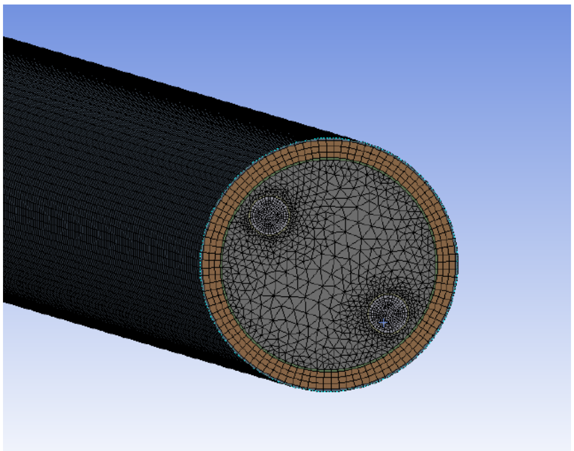

Fig. 2 (a) – Model's Mesh Structure

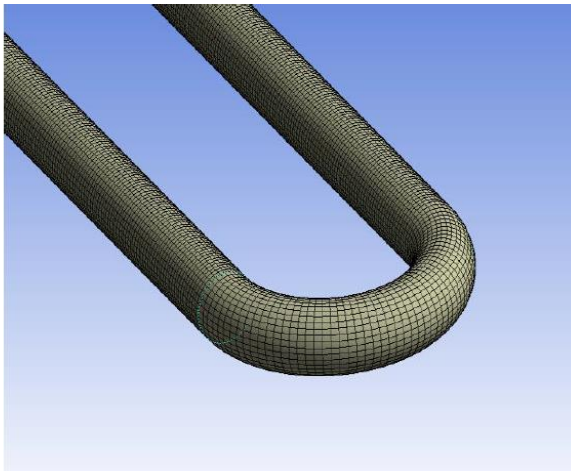

Fig. 2 (b) – Copper Pipe Mesh Structure

Meshing process is done with ANSYS software that is a commercial finite element solver. Fig. 2 (a) shows the isometric view of the mesh structure of the numerical model, and Fig. 2 (b) shows the mesh structure of the copper piping installation inside the evacuated tube structure. Here, hexa structured mesh is knitted for solid volumes. Due to the complexity of the model and the inability to reduce the solution time, the fluid volumes are knitted with a triangular mesh. The triangular mesh structure, which is created with the aim of increasing the mesh structure quality and reducing the solution time, is transformed into a polyhedral mesh structure by improving it in ANSYS-FLUENT, a commercial computational fluid dynamics software. This structure can be seen with Fig. 3.

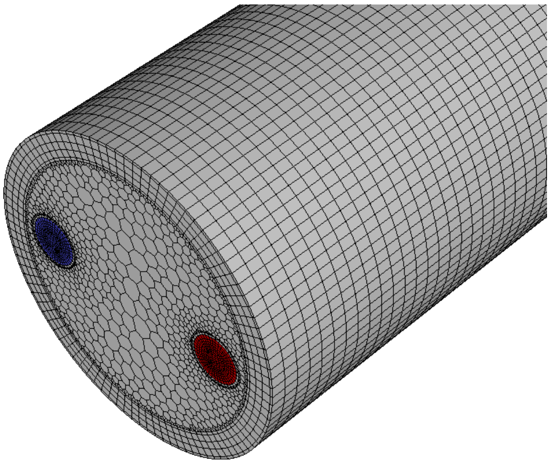

Fig. 3– Polyhedral Mesh Structure

The variation of the refrigerant outlet temperature according to the total number of cells in the mesh structure is given in Table-1. Based on these data, independence from the network structure was achieved with a total number of 7850000 elements for analysis.

Tab. 1 - Refrigerant outlet temperature values according to mesh size

Cell Number	Refrigerant Outlet Temperature [°C]
3750000	81.412
4300000	81.395
5600000	81.252
6000000	81.205
7500000	81.198
7850000	81.197

2.3 Boundary Conditions and Solution Method

While solving the three-dimensional numerical model of the evacuated tube collector examined within the scope of the study, the following assumptions are made

- The thermal losses by radiation and convection to the environment are neglected.
- Modelling of the vacuum field is possible by defining a very small value of conductivity and specific heat value to the relevant volume. For this reason, the thermal conductivity coefficient of the vacuum area is accepted as 10-18 W/mK [8].
- System is accepted in steady state regime
- Heat transfer by radiation between the concentric glass surfaces is neglected.
- The inner glass surface temperature is assumed constant throughout the calculation due to neglect of the variability of seasonal solar radiation.

The solution boundary conditions are given in Fig. 4 and explained in Table-2. The inlet temperature of the refrigerant to the collector varies for summer and winter conditions. The main reason for this can be shown as the change in compressor frequency according to the capacity requirement that the device must meet in different operating conditions. In addition, the inner glass surface temperature varies according to the efficiency of benefiting from solar radiation.

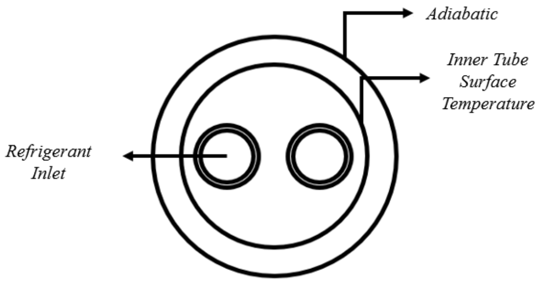

Fig. 4 – Boundary Conditions

Tab. 2 - Boundary conditions according to summer and winter conditions. [7]

Summer		Winter	
Parameter	Value	Parameter	Value
Refrigerant Inlet Temperature [°C]	80.2	Refrigerant Inlet Temperature [°C]	71.5
Inner Tube Surface Temperature [°C]	170	Inner Tube Surface Temperature [°C]	200

The thermophysical properties of the materials used in the analysis are shown in Table-3. These materials are evacuated tube's structure. The thermophysical properties (density, specific heat, conductivity, and viscosity) of the heat transfer fluid used in the analysis change depending on the temperature, and these properties are defined as a function of cell temperatures as a piecewise polynomial to the solver.

Tab. 3 - Thermophysical properties of the used material [8]

Material	Density [kg/m^3]	Heat Capacity [J/kg-K]	Conductivity [W/m-K]	Viscosity [kg/m-s]
Glass	2230	980	1.14	-
Vacuum	1.225	0.00001	1e-18	-
R410a	115.4	1327	0.02255	0.00001765

Conservation equations in cylindrical coordinates are discretized with the Power-Law scheme and solved with the SIMPLE algorithm. Conservation equations for cylindrical coordinates are generalized by Equation-1 [9].

$$\frac{\partial(\rho\varphi)}{\partial \mathrm{t}} + \nabla\left(\rho\varphi\vec{V}\right) = \nabla\left(\Gamma_{\varphi}\nabla_{\varphi}\right) + S_{\varphi} \quad (1)$$

Here, ρ, φ, $\vec{V}$, S_{φ} and Γ_{φ} are the fluid density, the independent parameter, the fluid velocity vector, the source term, and the effective diffusion coefficient, respectively. The refrigerant flow is modeled with the standard k-ε turbulence model. The energy equation is given with Equation-2 [9].

$$\frac{\partial T_f}{\partial t} + \vec{v}\nabla T_f = a_f(\nabla^2 T_f) \qquad (2)$$

Here T_f is the fluid temperature. The study is made for the steady-state condition, so the time dependent terms given by Equation-1 and Equation-2 are not included in the solution.

3. Results

The results obtained from the study is analyzed for four different heat transfer fluids (HTFs). In addition, these scenarios are evaluated separately for summer and winter working conditions.

Tab. 4 - Results

HTF	Working Condition	Surface Temperature with Air [°C]	Surface Temperature with HTF [°C]
Thermino l - 54	Winter	83.10	111.53
	Summer	90.96	117.53
Texol Texotherm HT - 32	Winter	83.10	112.16
	Summer	90.96	122.49
Diphyl DT	Winter	83.10	110.8
	Summer	90.96	116.8
Latema LT4	Winter	83.10	110.54
	Summer	90.96	116.57

The findings indicated in Tab. 4 is obtained as a result of five different analyses. First, in the absence of heat transfer fluid, the surface temperature of the copper pipe while there is air in the evacuated tube collector is examined, and then the surface temperature of the copper pipe by filling this space with four different heat transfer fluids is examined. In the findings, the heat transfer fluid Texol Texotherm HT -32 increased the surface temperature of the copper pipe by 35% compared to the empty state. The temperature distribution in the top view of the collector is given in Fig. 5 together with the empty collector and in the case of using this fluid together with Fig. 6.

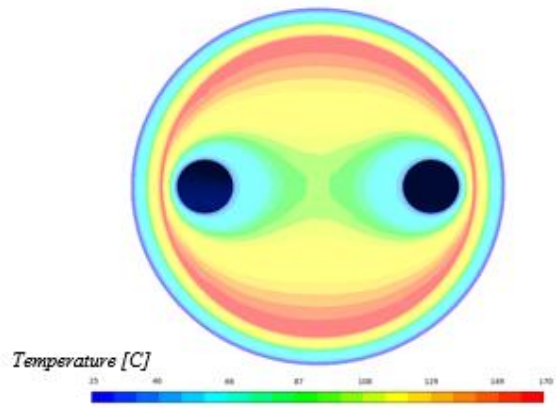

Fig. 5 (a) – Temperature distribution in empty evacuated tube, summer conditions

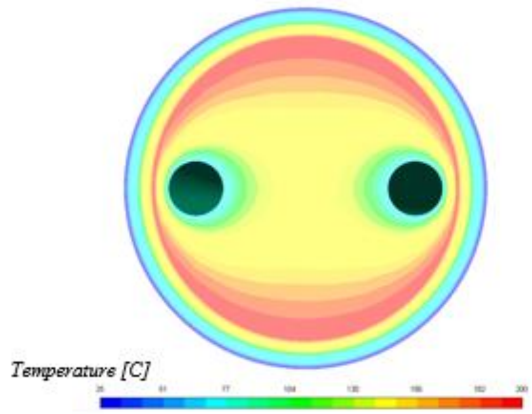

Fig. 5 (b) – Temperature distribution in empty evacuated tube, winter conditions

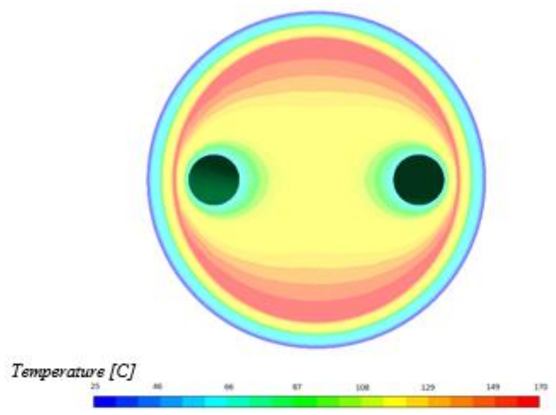

Fig. 6 (a) – Temperature distribution in evacuated tube with the use of heat transfer fluid, summer conditions

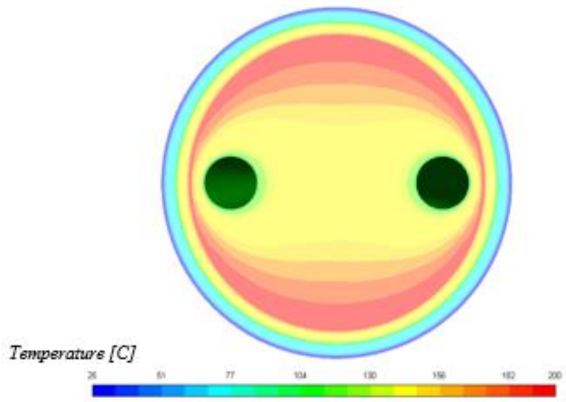

Fig. 6 (b) – Temperature distribution in evacuated tube with the use of heat transfer fluid, winter conditions

When Figure-6 is examined, it is seen that the thermal stratification formed in the space inside the tube decreases compared to an empty collector. However, it can be said that the amount of heat transfer to the copper pipe installation in the evacuated tube has increased. This situation shows that there is an increase in the amount of heat transfer to the refrigerant in the superheated vapor phase in the compressor discharge line. As shown in Tab. 4, the 35% increase in the surface temperature of the copper pipe supports this finding. With the use of Texol Texotherm HT -32 heat transfer fluid, it is observed that the fluid leaves the collector with a temperature increase of 1.02 ^{o}C. Increasing the temperature of the fluid with the thermal energy gained from the collector can be used to decrease the compressor operating frequency. Thus, a part of the condensation pressure (also the high pressure of the cooling cycle) that the compressor should create will be provided by the thermal input from the solar thermal energy.

Cost analysis studies show that the unit liter prices of Therminol - 54 Texol Texotherm HT 32, Diphyl DT and Latema LT4 heat transfer fluids are different from each other. The costs per liter for these fluids are given in Figure - 7. While Therminol - 54 and Texol Texotherm HT 32 fluids have the same unit cost, the unit cost of other fluids is higher.

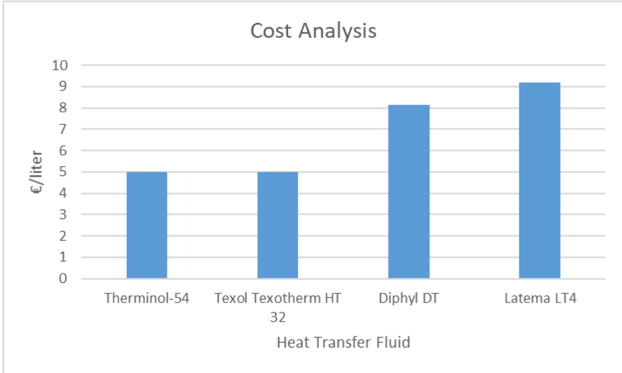

Fig. 7 – Cost analysis of heat transfer fluids

4. Conclusions

In this study, numerical analysis of evacuated tube solar collector integrated into the discharge line of a rooftop unit is carried out using different heat transfer fluids. If the results obtained with the data obtained from the important findings are summarized,

- With the use of heat transfer fluid, temperature up to 35% is observed on the surface of the copper pipe. Due to the location of the collector within the framework of this analysis, the refrigerant in the superheated vapor phase circulates. Currently, providing heat transfer to the refrigerant in this state is a difficult process. For this reason, the space in the evacuated tube structure should be filled with a heat transfer fluid.

- With the use of heat transfer fluid, the thermal stratification between the supply and collection lines of the copper piping in the collector is reduced.

- Improving effect of the other heat transfer fluids used on the collector surface temperature is not far from the effect of the Texol Texotherm HT -32 heat transfer fluid, which is determined as the maximum.

- Results show that performance will be close to each other with all heat transfer fluids, but when cost analysis is made, it is seen that Texol Texotherm HT 32 or Therminol - 54 fluid has a financial advantage. This finding demonstrates that financial research is essential in such an analysis and in such a system design.

5. Acknowledgements

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