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Experimental Analysis of the Plate-on-Tube Evaporator on a Domestic Refrigerator's Performance

Mert Tosun, Tuğba Tosun

***Abstract*—**The evaporator is the utmost important component in the refrigeration system, since it enables the refrigerant to draw heat from the desired environment, i.e. the refrigerated space. Studies are being conducted on this component which generally affects the performance of the system, where energy efficient products are important. This study was designed to enhance the effectiveness of the evaporator in the refrigeration cycle of a domestic refrigerator by adjusting the capillary tube length, refrigerant amount, and the evaporator pipe diameter to reduce energy consumption. The experiments were conducted under identical thermal and ambient conditions. Experiment data were analysed using the Design of Experiment (DOE) technique which is a six-sigma method to determine effects of parameters. As a result, it has been determined that the most important parameters affecting the evaporator performance among the selected parameters are found to be the refrigerant amount and pipe diameter. It has been determined that the minimum energy consumption is 6-mm pipe diameter and 16-g refrigerant. It has also been noted that the overall consumption of the experiment sample decreased by 16.6% with respect to the reference system, which has 7-mm pipe diameter and 18-g refrigerant.

***Keywords*—**Heat exchanger, refrigerator, design of experiment, energy consumption.

I. Introduction

REFRIGERATORS are used extensively in domestic areas for providing suitable temperature for hygienic and cold storage of foods and beverages, as well as for ice production for more than a century. Refrigerators based on a vapor compression cycle consist of thermally sealed compartments for storage and cooling components of the cycle such as compressor, evaporator, condenser, capillary tube and the refrigerant. Evaporator is an important component which converts the liquid refrigerant to vapor by absorbing heat in the refrigeration cycle. The evaporators are used for variety of applications in cooling appliances and hence they are available in numerous shapes, sizes and designs. Evaporator is the most important component which frequently defines the system efficiency and capacity by absorbing heat from the foods to be cooled to the refrigerant of system.

The heat exchanger types which are used as evaporators in vapor compression cycles of household refrigerator/freezers are summarized as follows.

Rold-Bond orator which is used on refrigerators or freezers consists of a two welded metal plates with serpentine tube form between those plates. A nonsticking material in the form of desired serpentine shape is applied between these two metal sheets. Then, the plates are pressed so that the edges of the plates are welded together. Thanks to the nonsticking material, the serpentines are shaped naturally. Surface of the evaporator may be painted with white plastic powder if required. One side flat roll-bond evaporator, double side inflated roll-bond evaporator, partial one side flat roll-bond evaporator can be used for cooling systems.

Finned tube evaporators consist of tubes with extended sheets or fins to increase the heat transfer surface area for better performance. Tubes can be formed in staggered or inline layout. An inline tube geometry is rarely used because it provides considerably lower performance than the staggered tube geometry. The fins are placed between the tubes to support and enhance the heat transfer from the hot air to the relatively cold refrigerant. These evaporators have several types of fins which can be named as plate fin, spin fin, wavy fin, and louver fin. The tubes and fins are generally made of aluminum or copper. The finned tube evaporators are usually used for no frost type refrigerator/freezers.

Wire on tube shelf evaporators consists of serpentine tubes and wires on both sides of the tubes. The individual shelves are hard brazed together to form multi shelve units, commonly from 2 to 8. They are usually found in the multiplex upright freezers. Although they are expensive compared to the alternative evaporator types, they have a multi-functional feature such as combining shelves and the evaporator. Consumers can store their food directly on this kind of evaporators. Wire on tube shelf evaporators made from steel tube and wires to provide durability and better heat transfer performance.

Tube on sheet shelf evaporators are developed by using aluminum serpentine tubes and an aluminum plate and formed as freezer shelves ready to be assembled. Like wire on tube evaporators, these components can also be produced with different shelve numbers. As a result, this evaporator type is an economical alternative to wire on shelf tube evaporators in terms of multi-functionality.

One of these types is the plate on tube (POT) evaporators, which are commonly used in the conventional domestic refrigerators. This type of evaporators includes a single plate and a pipe through which the refrigerant flows. The plate acts as a fin, i.e. extended heat transfer surface and it helps to increase the heat transfer from the refrigerator space to the pipe. The pipe is attached to the plate in a form that allows to place as much pipe as possible to increase heat transfer rate, such as parallel passes from top to down as seen in Fig. 1. This type of evaporators is stuck on the polyurethane side of the

M. Tosun is with Arcelik A. S. Refrigerator Plant, Odunpazari 26110 Eskisehir, Turkey (phone: 00905498119395; e-mail: merttosun@ gmail.com).
T. Tosun is with the Eskisehir Teknik University 26130, Eskisehir, Turkey (e-mail: drtugbatosun@gmail.com).

plastic back wall of the refrigerator. The heat is absorbed in the compartment via the cold surface of the back wall which includes evaporator. In this type of evaporator, tubes and plates are commonly made from aluminum. POT evaporators are mainly used for cooling of the fridge compartments because of their cooling capacity and low cost.

Plate type evaporators in different geometries were investigated numerically using Computational Fluid Dynamics (CFD) method to reach a design which has increased heat transfer capacity by Todorov et al. [1]. The authors analyzed different pipe layouts and pipe cross sections. They conducted that a spiral layout with maximum heat transfer cross section gave the best heat flux.

Three kinds of flow path layout, two kinds of tube diameter and two types of refrigerant were used to compare the heat transfer performance of evaporators in the air conditioner by Jin et al. [2]. The evaporator has 7 mm tube diameter with two branches of refrigerant R22 is improved the new evaporator which had five branches. The cooper tube diameter was changed as 5 mm and refrigerant R22 was replaced to R290. Results showed that the energy efficiency of three kinds of flow path arrangements of R290 evaporator with 5 mm tube diameter is better than that of R22 system with 7 mm.

Jayakody et al. [3] developed a mathematical model to simulate and investigate the performance change of the heat transfer rate when the tube diameter and number of tubes are changed in cross flow steam condenser. The heat transfer rate was analyzed by changing the number of longitudinal tubes (varied between 10 and 60), tube diameters (19 mm, 25 mm and 32 mm) and the number of transverse tubes (varied between 5 and 55). They found that when the number of longitudinal tubes increases, heat transfer rate increases and change of the heat transfer rate decreases. Also noticed that heat transfer rate increases linearly when the number of transverse tubes increases while keeping the number of longitudinal tubes constant. Increasing the number of transverse tubes was found to be more effective than increasing the number of longitudinal tubes.

Gorobets et al. [4] examined hydrodynamics and heat transfer processes in heat exchangers with a compact arrangement of small diameter tubes theoretically and experimentally. Numerical modeling of heat transfer processes and hydrodynamics for turbulent flow of heat-carrier and experimental investigations of hydrodynamic and heat transfer characteristics of new designs of heat exchangers with compact bundles of small diameter tubes were carried out. They found from the results that the proposed designs of shell-and-tube heat exchangers have dimensions of 1.7-2 times smaller, and mass is 10-15 % lower compared to heat exchangers of traditional designs with the same heat power.

Effect of coil diameter on the melting process of phase change material of the shell and spiral tube heat exchanger was investigated by Rahimi et al. [5]. Shell and tube heat storage unit (HSU) with spiral tube was filled with phase change material (PCM). Performance of HSU was examined for three different Stefan numbers (0.43, 0.48, and 0.53) and coil diameters were chosen as 5, 7, and 9 cm. They found from the experiment results that increasing coil diameter causes a decrease in total melting time and an increment in final average temperature of PCM. They also indicate that by increasing of Stefan number melting process accelerates and total melting time decreases.

Although there are plenty of studies about other evaporator types in the literature as mentioned in the previous paragraphs, plate tube evaporator usage in the refrigerators has not been scrutinized deeply.

In this study, the performance of the plate tube evaporator has been investigated by changing evaporator pipe diameter, capillary tube length and refrigerant amount on the energy consumption of the refrigerator.

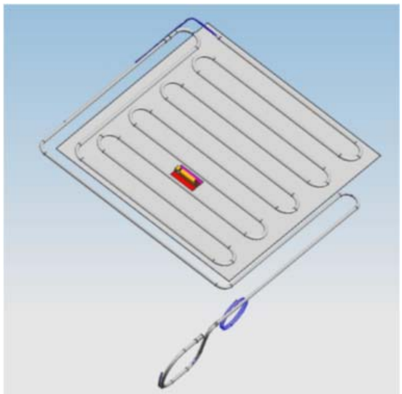

Fig. 1 POT evaporator

II. SETUP

The parametric experimental setup has been established in order to determine the most significant parameter which affects the cooling performance of the evaporator in a fridge. The fridge used in the experiments has 135 L gross volume and provides cooling by natural convection. The compressor used in the system is an R600a compressor which has 90 kcal/h cooling capacity and 1.66 W/W COP. The POT evaporator is attached to the backwall of the body of the refrigerator cabinet inside the insulation material. The plastic surface in which the evaporator is positioned is in contact with air and it provides heat transfer by natural convection. Evaporator consists of 480 mm x 420 mm aluminum plate and 6434 mm of aluminum pipe. POT evaporator is given in Fig. 1.

According to the IEC 62552 standard which defines characteristics and test methods for household refrigerating appliances, the experiments are executed in a climatic chamber at 25 °C ambient temperature. Energy consumption is measured while fresh food compartment average air temperature is 5 °C. Power consumption is measured by using Ohio brand power sensor and energy consumption is measured ION brand sensor. FLUKE 5500 calibrator is used to calibration of thermocouples, power and energy sensors. The uncertainties of devices are given in Table I.

The experiments were carried out in a climatic chamber in order to stabilize the ambient air conditions as required by the mentioned international standard. In the experimental design, evaporator pipe diameter, capillary tube length and refrigerant amount were determined as the parameters. Thus, the investigations focused on finding the right size of evaporator, the capillary tube length and weight of the refrigerant in order to find the optimum performance of this brand-new product. DOE method which is one of the effective methods of 6 sigma methodology has been used in the analysis of the experimental results. According to DOE, total of 24 different configurations were planned for the experimental study. Three different evaporator pipe diameters, two different capillary pipe lengths, and four different refrigerant amounts were selected for the tests. The variation of parameters is given in Table II.

TABLE I
UNCERTAINTY ANALYSIS

Measuring device	Brand	Uncertainty (%)
Power sensor	Ohio	0.05
Energy sensor	ION	0.2
Voltage sensor	Ohio	0.25
Current sensor	Ohio	0.25
Thermocouple	-	0.4

TABLE II
PARAMETERS USED IN DOE

Evaporator Pipe Diameter (mm)	Capillary Tube Length (mm)	Refrigerant Amount (gr)
5	2000	12
6	2500	14
7		16
		18

III. RESULTS

Energy consumption of domestic fridge for the three types of parameters such as evaporator pipe diameter, capillary length and refrigerant amount has been analyzed in the climatic chamber as presented previously. Experiments were carried out while fresh food compartment average air temperature is 5 °C according to related standard at 25 °C ambient temperature in a climatic chamber. In order to determine main and mutual the effects of parameters on the cooling performance and energy consumption of domestic fridge, 24 different cases have been tested for domestic table top fridge. Every configuration has been measured two times for verification of parameters. Experimental results of the fridge are summarized in Table III.

The effect of parameters has been investigated by using "General Linear Method", GLM. GLM is s a statistical linear model, which quantifies the relationship between several independent or predictor variables and a dependent or criterion variable. The effect of the parameters on energy consumption has been shown in Fig. 2.

It has been seen from the results that the most significant parameters are refrigerant amount (70.3%) and evaporator pipe diameter (10.76%). The mutual (combined) effects of capillary tube length and refrigerant amount, and evaporator pipe diameter and capillary tube length were seen 4.3% and 2.5%, respectively.

TABLE III
EXPERIMENTAL RESULTS

Evaporator Pipe Diameter (mm)	Capillary Tube Length (mm)	Refrigerant Amount (gr)	Energy Consumption (kWh/24h) First Test	Energy Consumption (kWh/24h) Second Test
7	2000	18	0.424	0.428
6	2000	18	0.359	0.357
5	2000	18	0.398	0.396
7	2000	16	0.389	0.392
6	2000	16	0.358	0.357
5	2000	16	0.377	0.38
7	2000	14	0.389	0.387
6	2000	14	0.386	0.383
5	2000	14	0.395	0.395
7	2000	12	0.422	0.424
6	2000	12	0.446	0.447
5	2000	12	0.458	0.46
7	2500	18	0.392	0.395
6	2500	18	0.356	0.355
5	2500	18	0.404	0.401
7	2500	16	0.387	0.388
6	2500	16	0.36	0.357
5	2500	16	0.37	0.371
7	2500	14	0.432	0.435
6	2500	14	0.386	0.384
5	2500	14	0.383	0.382
7	2500	12	0.512	0.508
6	2500	12	0.461	0.457
5	2500	12	0.455	0.456

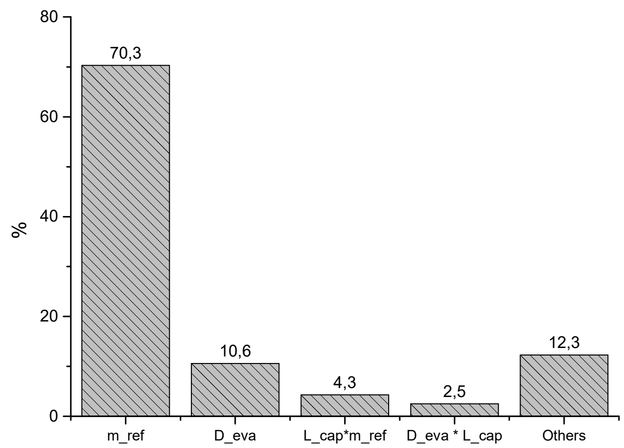

Fig. 2 The effect of parameters on energy consumption by General Linear Method Analysis

The minimum energy consumption has been observed when refrigerant amount is 16 gr, as seen in Fig. 3. The highest energy consumption is measured when the refrigerant amount is 12 g. This result is expected since the evaporator has not been completely filled with liquid refrigerant and the refrigerant has reached super-heated phase before the evaporator exit (last pass).

According to the results shown in Fig. 4, evaporator pipe with 6-mm diameter gave the lowest energy consumption. 5-mm pipe diameter resulted in the second best consumption, while 7-mm pipe diameter increased the consumption to the top.

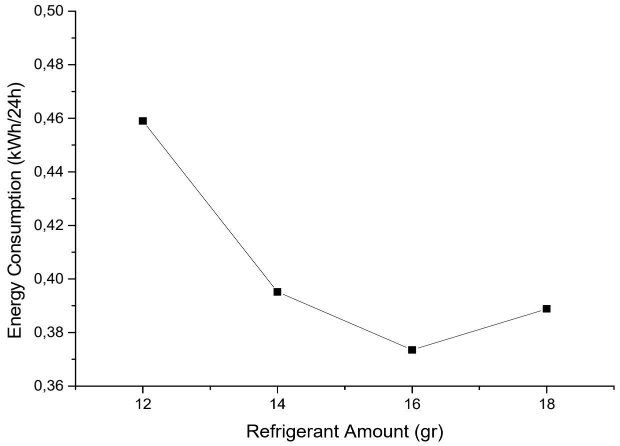

Fig. 3 The variation of the energy consumption with refrigerant amount

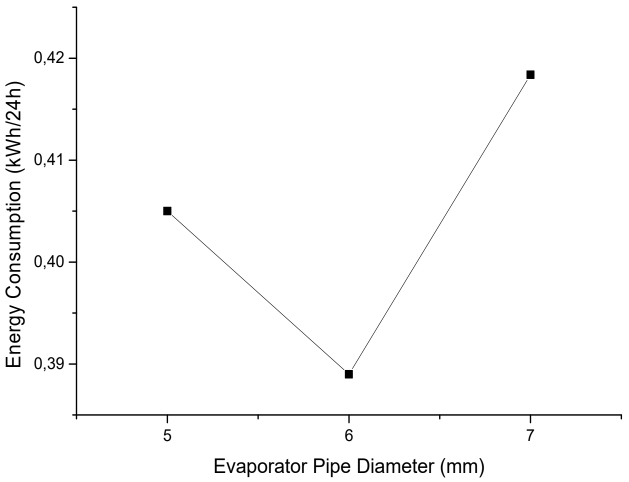

Fig. 4 The variation of the energy consumption with evaporator pipe diameter

The interaction of capillary tube length and refrigerant amount with variation of energy consumption, given in Fig. 5, when the refrigerant amount is 18 gr, 2500 mm capillary tube length has provided the lowest energy consumption. On the other hand, when the refrigerant amounts are 12gr or 14 gr, 2000 mm capillary tube length has provided the lowest energy consumption. In the configurations which include 16 gr refrigerant amount, capillary tube length has been found to be non-effective on energy consumption. The lowest energy consumption has been provided with 16 g refrigerant amount.

The graph included the interaction of capillary tube length and evaporator pipe diameter with variation of energy consumption is given in Fig. 6. The result of energy consumption has been found similar with 2000 mm and 2500 mm capillary tube lengths when evaporator pipe diameter is 6 mm. It can be considered that capillary tube length is not effective on the energy consumption while the evaporator pipe diameter is 6 mm. When evaporator pipe diameters are 5 mm and 7 mm, it has been seen that capillary tube length is more effective according to 6 mm evaporator pipe diameter. When the evaporator pipe diameter is 7 mm, the effect of capillary tube length on the energy consumption has been calculated %6.3 approximately.

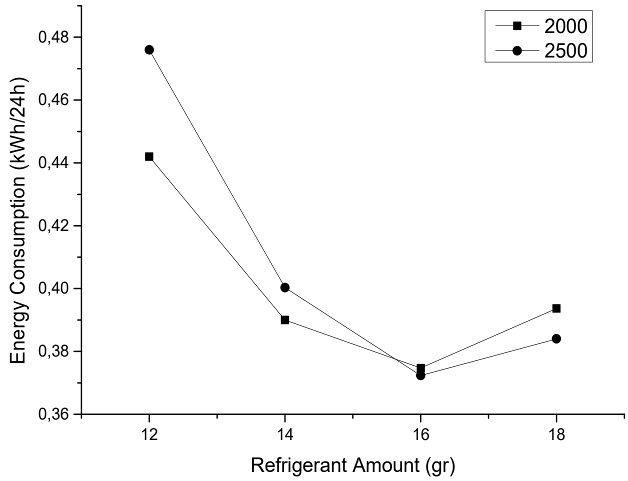

Fig. 5 The variation of the energy consumption with the interaction of capillary tube length and refrigerant amount

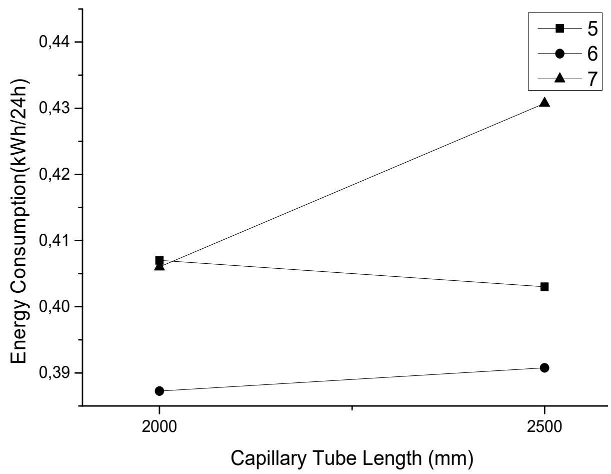

Fig. 6 The variation of the energy consumption with the interaction of capillary tube length and evaporator pipe diameter

As a result, in the experiments that the system is optimized daily energy consumption has been found as 0.357 kWh/24h when the configuration includes 6 mm evaporator pipe diameter and 16 gr refrigerant amount.

IV. Conclusion

In this study, the influence of the evaporator pipe diameter, capillary tube length and refrigerant amount on the performance of the table top fridge has been aimed to investigate experimentally. The energy consumption tests were carried out for 24 different configurations according to IEC 62552 standard. According to the results of the experiments, refrigerant amount (70.3%) and evaporator pipe diameter (10.76%) have been determined as the most essential parameters effects the POT evaporator cooling performance and energy consumption of the fridge. The mutual (combined) effects of capillary tube length and refrigerant amount, and evaporator pipe diameter and capillary tube length were seen 4.3% and 2.5% respectively. In summary, in the experiments that the system is optimized daily energy consumption has been found as 0.357 kWh/24h when the configuration includes 6 mm evaporator pipe diameter and 16 g refrigerant amount.

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