Optimization of Heat Transfer Performance in Freezer Room with Computational Fluid Dynamics Approach

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Abstract—**It is a legal requirement that refrigerators display an energy label indicating the level of energy efficiency, with a minimum of one star. In order to fulfil the aforementioned requirement, it is necessary to modify the evaporator fin pipe arrangement, changing its design from inlined to staggered. A Computational Fluid Dynamics (CFD) method was employed to analyse the heat transfer performance of the evaporator fin and its impact on electrical power consumption. The study employed a two-door refrigerator model that adheres to the specifications outlined in the International Electrotechnical Commission (IEC) 6225:2015 standard. Computational fluid dynamics (CFD) simulations were conducted in two phases. The initial phase of the study sought to ascertain the mean temperature of the evaporator fin, demonstrating that the staggered pipe configuration proved more efficacious than the inlined alternative. The second phase of the study evaluated the cooling time required to reduce the temperature from 32°C to -7°C. The electrical power consumption and daily operation times for the inlined and staggered pipe arrangements were 1.23 kWh and 12.3 hours, and 1.08 kWh and 10.08 hours, respectively.**

Keywords—Refrigerator; Inlined; Staggered; CFD; M-packages

I. Introduction

The application of cooling is pervasive across a multitude of processes, encompassing air conditioning and human comfort, among other areas. A prominent example of a cooling device is the refrigerator. The use of refrigerators and freezers is a common practice in the preservation of foodstuffs, whereby the food is maintained under conditions that are specifically tailored to the intended use [1], [2], [3], [4], [5]. The cooling process in refrigerators is carried out by storing objects in a room at a temperature below that of the surrounding environment, according to the cooling load [6]. This slows down the decay process and extends the shelf life of the stored items.

In the primary refrigeration loop, the refrigerant is subjected to compression from the low-pressure side to the high-pressure side. Subsequently, the cooled liquid is returned to the low-pressure receiver via the expansion valves[7], [8]. The utilization of refrigerators in both domestic and industrial contexts entails the vapor compression cycle. Vapor compression refrigeration systems are commonly employed for the provision of a cool atmosphere in the context of space thermal conditioning control in commercial and industrial applications. These systems are comprised primarily of a compressor, a fixed-orifice expansion device, two heat exchangers (such as an evaporator and a condenser), and the light secondary fluid known as refrigerant, which readily evaporates and condenses [9]. The evaporator is comprised of three principal components: a heat sink, an evaporation section, and a separator, which is responsible for the separation of the vapor from the liquid prior to its transferal to the condenser. The utilization of evaporator systems in industrial contexts is significant, as they are capable of facilitating the transfer of components with disparate boiling points without the necessity for the introduction of additional chemicals that have the potential to impact product quality. The global demand for refrigerators is experiencing a continuous annual growth. According to data from statista.com, the average household is expected to own 0.09 units of refrigerators by 2024, representing an estimated increase of 2.1% by 2025. It is projected that the total volume of refrigerators will reach 206.4 million units by 2028. Furthermore, the aforementioned statistics illustrate an escalation in electrical power consumption, a consequence of the augmented utilization of refrigerators. The trade of refrigerators in Indonesia is subject to regulation in accordance with the level of electrical energy consumption.

Engineers encounter obstacles when attempting to modernize designs and incorporate novel concepts with the objective of enhancing the efficiency of refrigeration systems. A primary objective is to develop an efficacious refrigeration design that can optimize heat transfer to enhance cooling velocity and curtail energy consumption. One component that is frequently re-engineered is the fin on the evaporator, which plays a pivotal role in this process. The function of the fin is to facilitate the absorption of heat from the cooling room, thereby reducing the temperature. It has been demonstrated that the freezing of the finned pipe enhances the transfer of heat and reduces the resistance to airflow. An effective fin design on the evaporator fin serves

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to reduce electrical energy consumption by enhancing cooling efficiency [10].

Computational Fluid Dynamics (CFD) is a study that uses numerical analysis to solve mathematical equations in order to understand fluid flow, heat transfer, chemical processes, and other topics. It is beneficial for both starting from scratch when constructing a heat exchanger system and for troubleshooting/optimization by making design modification [11]. The very basic idea behind CFD is to solve the system as a whole in small cells or grids and then apply governing equations to these discrete elements to find numerical solutions for things like temperature gradients, flow parameters, pressure distribution, and the like in a shorter amount of time and at a lower cost because less experimental work is needed [12], [13] . As an example of the use of CFD, the research conducted by Quitiaquez focused on increasing or improving the use of solar energy. This involved managing the heat flow, where CFD software was used to validate the temperatures achieved [14]. This study uses the Computational Fluid Dynamics (CFD) method with SOLIDWORKS flow simulation software. CFD is an approach with computer simulation to analyze fluid behavior based on conservation laws (mass, momentum, and energy).

Numerical simulation studies of household refrigerators using computational fluid dynamics (CFD) have garnered attention due to their effectiveness in accurately predicting air temperature and velocity distribution within the simulated compartments [15]. Accurate simulation is crucial for assessing thermal performance across different operating conditions and for achieving optimal design. Computational Fluid Dynamics (CFD) is highly suitable for examining fluid flow design, static and thermal analyses, and achieving design improvements tailored to specific requirements. Moreover, valid CFD modeling enhances analysis flexibility and provides highly detailed data. Through precise simulation, in-depth optimization of heat exchanger design can be effectively accomplished.

The refrigerator was modelled and simulated using CFD. Comparing the thermal performance of a reference refrigerator with a finned surface versus a suggested design with a smooth surface was the primary goal [16], [17]. They focused specifically on the freezer section of a natural convection refrigerator. Through experimentation and Computational Fluid Dynamics (CFD), they analyzed 17 different models to optimize the temperature distribution within the freezer [18]. The CFD validation shows satisfactory outcomes for designing and enhancing compact heat exchangers, as evidenced by Abeykoon's study. It illustrates that such validation can be applied to various design options without the need to create prototypes using fluids with different thermodynamic properties [19].

Refrigerator freezers are crucial for keeping perishable food fresh in hot and humid environments [20], [21]. Tests were carried out in a controlled setting to examine how factors like surrounding temperature, cabinet load, thermostat adjustment, and an open water pan affect the heat transfer and energy use of refrigerators [22]. This study is based on the one conducted by Laguerre et al., to gain a better insight into the air flow and heat transfer inside a refrigerator. Three configurations were studied: an empty refrigerator with and without shelves, and a loaded refrigerator. The aim was to measure the air temperature and velocity distribution in the refrigeration compartment in the presence of obstacles (shelves and products) and compare the results with those obtained using an empty compartment [23].

Although the power consumption of a single household refrigeration appliance appears to be low, the savings potential of the entire fleet is considerable due to the almost complete market penetration and typical continuous operation. In total, over 1.500 billion household refrigerators and freezers are in use worldwide, accounting for approximately 4% of global electricity consumption, annually causing 480 million tons of CO2 equivalent [24]. Given these considerations, refrigerator manufacturers were required to comply with regulations on product power consumption. The rules mandated that refrigerators include an energy label with at least one star to remain market viable. The objective of this research is to analyses the efficiency of heat transfer in an effective evaporator fin [25]. This study compares two pipe designs commonly employed in refrigerators: the inlined (parallel) and the staggered (crossed or angled) arrangement. The study was conducted using a two-door refrigerator, which is one of the best-selling products on the market. The findings of this study may prove beneficial to both consumers seeking information and refrigerator manufacturers engaged in the development and enhancement of their products.

II. MATERIALS AND METHODS

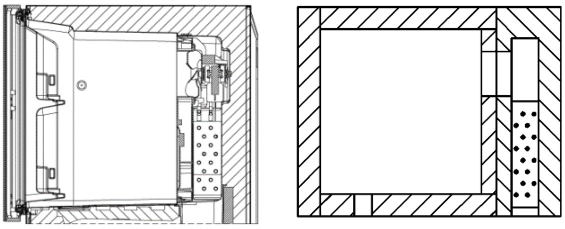
A. Material

The research object was a two-door refrigerator. The research was conducted on the freezer compartment, which was designed in a simplified manner to facilitate computational fluid dynamics (CFD) simulation. The dimensions (WxDxH) of the freezer room were determined based on the actual dimensions of the room in question. The positions of the fin evaporator and blower fan were maintained in accordance with their original locations within the refrigerator. The specifications of the freezer room employed for the CFD simulation process were as follows:

1. The dimensions of the freezer room are as follows: 405 x 360 x 370 mm (WxDxH).

2. The dimensions of the blower fan are as follows: Ø100 mm

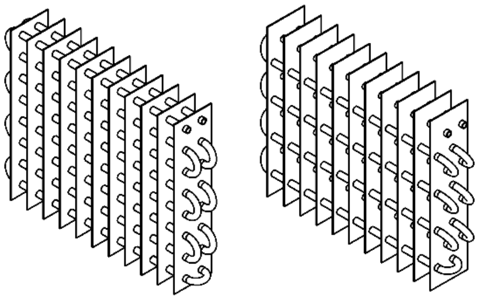
3. Dimensions of ducting hole are as follows: 100 x 40 mm.



(a) (b)

Fig. 1. (a) Section view of frezzer room (b) Section view of frezzer room for CFD simulation

The fin evaporator, the subject of the present study, is comprised of two distinct types: those with inlined and staggered pipe arrangements, which exhibit an identical fin spacing of 7.5 mm and are constructed from aluminum with external dimensions of 265x60x238 mm (WxDxH). These specifications are employed in the CFD simulation process for the purpose of conducting a heat transfer analysis.



(a) (b)

Fig. 2. (a) Fin evaporator with inlined pipe arrangements (b) Fin evaporator with staggered pipe arrangements

B. Methods

A validation study was conducted to compare the results of temperature changes on the fin surface and freezer chamber when performing computational fluid dynamics (CFD) simulations using fin evaporators with inlined and staggered pipe arrangements. In the heat transfer simulation, the initial temperature of the fin surface is set at 32°C in accordance with the IEC 6225-2/2015 standard, while the flowing fluid is assigned a temperature calculated using CFD simulation. The simulation data, presented in the form of curve diagrams and displaying the results of the CFD simulation once convergence has been reached, is employed for comparison.

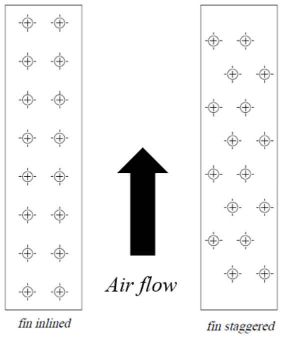


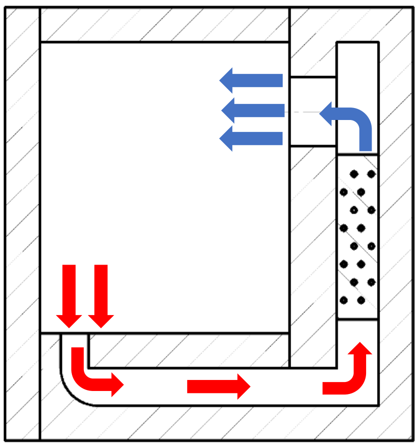
Fig. 3. Air flow movement

Subsequently, a comparative validation was conducted to assess the cooling velocity between the two freezer chambers through the utilisation of computational fluid dynamics (CFD) simulations.

1. The initial freezer chamber employs a fin evaporator with an integrated pipe configuration.
2. The second freezer chamber employs a fin evaporator with a staggered pipe configuration.

A series of simulations were conducted with the objective of approximating the actual conditions that would be encountered in freezer room temperature conditioning. This configuration is founded upon the observation design, test data, and consultation, which collectively represent the research parameters. The simulation conditioning process comprises the following steps:

- The air within the freezer room is circulated through the blower fan and ducting in accordance with the original design of the refrigerator. The air flow is regulated by the blower fan to control the movement of incoming and outgoing air, which affects the heat exchange in the freezer room with the fin evaporator, thereby lowering the room temperature. An overview of the incoming and outgoing air flow is provided in Figure 4.



 = The air from the evaporator fin enters the freezer room through the blower fan hole.

 = The air from the freezer room is conveyed back to the fin evaporator via the ducting hole.

Fig. 4. Air circulation in the freezer room

III. RESULTS AND DISCUSSION

A CFD analysis is conducted at specific temperature points within the freezer room, which are divided into temperature provision points and temperature measurement points. The assignment of CFD analysis points is performed in two phases:

1) The objective of Phase 1 is to ascertain the temperature of the area situated behind the blower fan and surface of fin plate. The temperature administration point is set at the hole located beneath the evaporator fin, with a temperature of 32 °C. Temperature measurement points are established at locations A and B within freezer room 1, and at points Y and Z within freezer room 2. Data results are subsequently obtained, and CFD simulations are conducted until convergence conditions with the steady state method are met. The results of the simulation will be employed in the subsequent phase of the simulation.

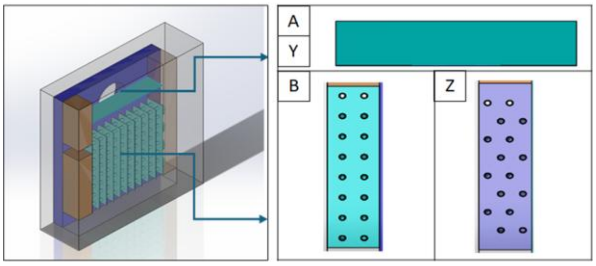


Fig. 5. Freezer area measurement point division

TABLE 1. TABLE FREEZER ROOM

Description	
A	Surface on the back of blower fan for Inline arrangement
B	Surface on fin surface for Inline arrangement
Y	Surface on the back of blower fan for Staggered arrangement
Z	Surface on fin surface for Staggered arrangement

2) Phase 2: The objective of Phase 2 is to determine the cooling time required to reduce the temperature of the freezer room to -7°C using m-packages. The temperature administration point is set according to the specifications of the blower fan hole, with the temperature itself being set in accordance with the findings of the preceding phase of simulations. The second phase of temperature measurement is conducted at four points in accordance with the specifications set forth in IEC 6225-2:2015. The simulation results are converted into energy labels

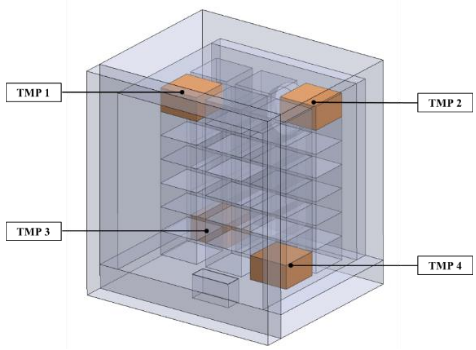


Fig. 6. Position of m-packages

The M-Packages are to be situated in the following positions:

TMP1 : Front left top corner

TMP2 : Rear right top corner

TMP3 : Front right bottom corner

TMP4 : Rear left bottom corner

The simulation was conducted on the area situated behind the blower fan and the fin surface, which is located at the centre of the evaporator. The temperature data was obtained from the colour graph situated at the centre axis of the blower fan. The data collected represents the temperature change after reaching the convergence condition, defined as a point at which the temperature no longer exhibits significant fluctuations or a temperature change difference of less than or equal to 2°C ($\Delta t \leq 2$°C).

The initial phase of the simulation entails the preparation of three-dimensional models, including those representing the mechanical room, evaporator fins with an inlined and staggered pipe configuration, and other pertinent data. The process entails the specification of parameters within the flow simulation software, the construction of enclosures, the input of data, and the pursuit of the desired outcomes. The software employs a solver to generate CFD simulations. The outcomes of the CFD simulations for the fin evaporator with both pipe arrangements were evaluated during the model validation stage.

The settings and data input in Flow Simulation software were modified to align with the specifications of the 2-door refrigerator. The aforementioned data is employed to establish parameters, including material, pressure, temperature, simulation conditions, convergence of simulation results, and specifications of components within the mechanical room and evaporator fin. The implementation of the aforementioned requirements with respect to the flow simulation settings and inputs is illustrated in Table 2 and Table 3.

The CFD simulation process utilises the Flow Simulation software, which employs a number of parameter settings to regulate the flow of fluids. These include the designation of a project name, the specification of a unit system, the definition of an analysis type, the selection of a default fluid, the designation of a default solid, the delineation of wall conditions, and the definition of initial conditions. The project name serves to identify the project in question during the course of the simulation. The system of units employed is NMM (mm-kg-s), with temperature recorded in degrees Celsius (°C) and time in minutes (min).

The selected analysis type is internal analysis, which indicates that the CFD simulation is performed within the mechanical room system. The "consider closed cavities" feature is employed to exclude empty spaces devoid of airflow, which are then treated as solid bodies. The physical features defined include the conduction of heat in solid materials, such as those situated behind the blower fan and on the fin surfaces.

The default fluid is pure air, while the flow types employed are laminar and turbulent, in order to encompass the full range of indoor airflow conditions. The default solid is focused on major components, such as pipes and evaporator fins, which are constructed from aluminium.

The initial conditions of the simulation are as follows: a pressure of 1 ATM (approximately 101325 Pa), an initial air temperature of 32 °C (in accordance with the default setting), and the initial temperature of the solid is equalised to the air temperature. A detailed description of these parameter settings can be found in Table 2 and Table 3

TABLE 2. TABLE OF PARAMETER SETTING SOLIDWORKS FLOW SIMULATION PHASE 1

Parameter tree	Setting parameter
Project name	Simulation Inline Phase 1
	Simulation Staggered Phase 1
Unit system	SI (m-kg-s)
	-Parameter temperature = Celsius (°C)
	-Parameter physical time = Minute (min)
Analysis type	-Analysis type
	Internal
	-Consider close cavities
	Exclude cavities with flow condition
	-Physical features
	Heat conduction in solid
	Gravity in Y axis = -9.810 m/s²
Default fluid	-Gases
	Air
	-Flow type
	Laminar and turbulence
Default solid	-Alloy
Parameter tree	Setting parameter
Project name	Simulation Inline Phase 1
Unit system	Simulation Staggered Phase 1
	SI (m-kg-s)

TABLE 3. TABLE OF PARAMETER SETTING SOLIDWORKS FLOW SIMULATION PHASE 2

Parameter tree	Setting parameter
Project name	Simulation Inline Phase 2
	Simulation Staggered Phase 2
Unit system	SI (m-kg-s)
	-Parameter temperature = Celsius (°C)
	-Parameter physical time = Minute (min)
Analysis type	-Analysis type
	Internal
	-Consider close cavities
	Exclude cavities with flow condition
	-Physical features
	Heat conduction in solid
	Gravity in Y axis = -9.810 m/s²
Default fluid	-Gases
	Air
	-Flow type
	Laminar and turbulence
Default solid	-Polymers
	Polystyrene (PS)
Unit system	-Thermodynamic parameters
	Parameter = Pressure , Temperature
	Pressure = 101325 Pa
	Temperature = 32°C

A. Phase 1

The input data for computational fluid dynamics (CFD) simulation with Flow Simulation is comprised of several principal components. The solid materials comprise the materials used for the construction of the internal components of the mechanical room, including the freezer cabinet walls, which are made of polyurethane (PU), the evaporator fins and pipes, which are made of aluminium, and the mechanical room partitions, which are made of polystyrene (PS). The temperature at several key points is determined by the boundary conditions, including the surface of the evaporator fin and pipe, the point under the evaporator fin, and the air outlet of the blower fan in the mechanical room partition. The objective is to obtain data on temperature changes at the top surface of the evaporator fin using fluid goals and at the evaporator fin surface using solid goals, once convergence conditions have been reached in the CFD simulation. The specific inputs for Flow Simulation are outlined in Table 2 and Table 3.

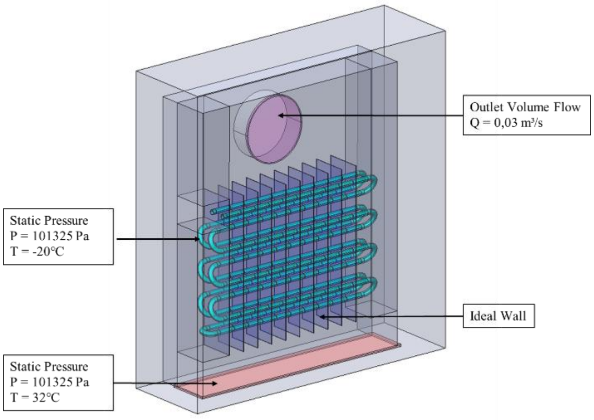
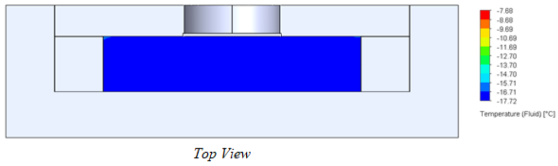


Fig. 7. Determination of boundary conditions in the simulation

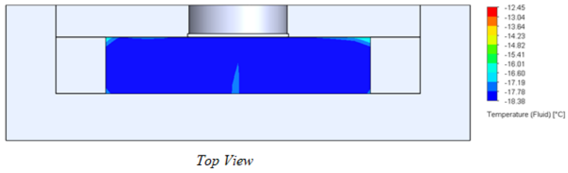
In the initial phase of the computational fluid dynamics (CFD) simulation, two models of fin evaporators were evaluated: an inlined fin type and a staggered fin type. This variation is conducted in order to obtain data on the analysis of the simulation results of the comparison of fin type performance on heat transfer in the evaporator through system modelling, with the aim of obtaining the temperature at point A and Y. The first phase variation is carried out by inputting a 3D mechanical chamber model with two different types of fin evaporators, each of which is tested with the parameters described in Table 2 and Table 3. The length of time the test is carried out until it reaches a convergent temperature is in accordance with the International Electrotechnical Commission (IEC 62552-2: 2015) standard.

TABLE 4. TABLE OF SIMULATION RESULTS PHASE 1 FOR POINT A AND Y

Fin Type	Inlined	Staggered
Iterations	148	144
Temperature (Min)	-17.715	-18.376
Temperature (Max)	-7.686	-12.451
Average	-12.701	-15.414
Physical Time (minutes)	14.800	14.400
CPU Time (minutes)	0.460	0.490



(a)



(b)

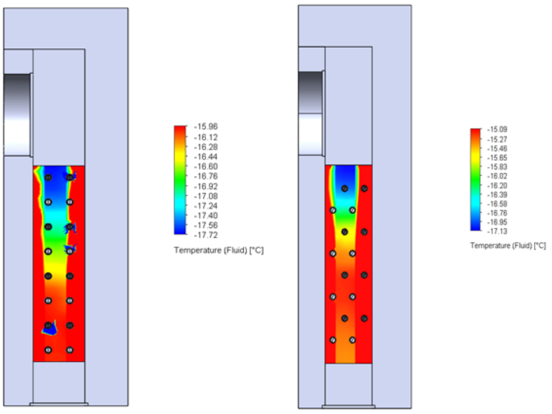
Fig. 8. Simulation results phase 1 for point c : a) inlined b) staggered

Table 4 presents the findings of the initial phase simulation utilising an evaporator with an inlined fin model. The cooling process in the inlined fin model takes a physical time of 14 minutes and 8 seconds and reaches an average convergence temperature of approximately -12.700°C and the results of the first phase simulation utilising an evaporator with a staggered fin model. The cooling process in the staggered fin model occurs in 14 minutes and 4 seconds, reaching the lowest temperature of approximately -15.410°C. This is a faster process than that observed in the inlined fin model.

The simulation results demonstrate that the staggered fin model exhibits a more efficient cooling process, with a shorter time to reach a lower convergence temperature. The more uniform distribution of heat in the staggered configuration reduces the likelihood of the formation of stagnant zones, where the airflow is inadequate to effectively absorb heat, as observed in the inlined configuration [26].

TABLE 5. TABLE OF SIMULATION RESULTS PHASE 1 FIN

Fin Type	Inlined	Staggered
Iterations	148	144
Temperature (Min)	-17.715	-17.134
Temperature (Max)	-15.963	-15.089
Average	-16.839	-16.112
Physical Time (minutes)	14.800	14.400
CPU Time (minutes)	0.460	0.490



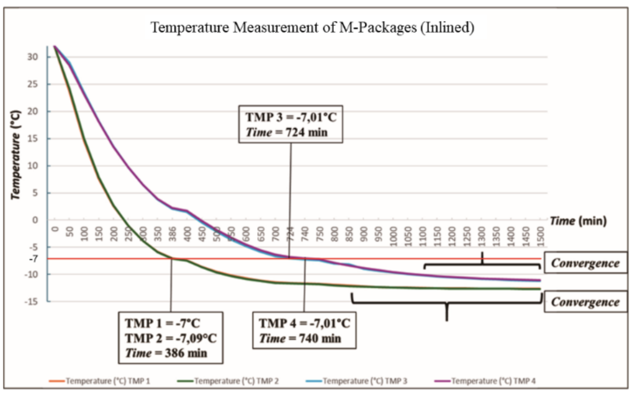
(a) (b)

Fig. 9. Simulation results phase 1 fin: a) inlined b) staggered

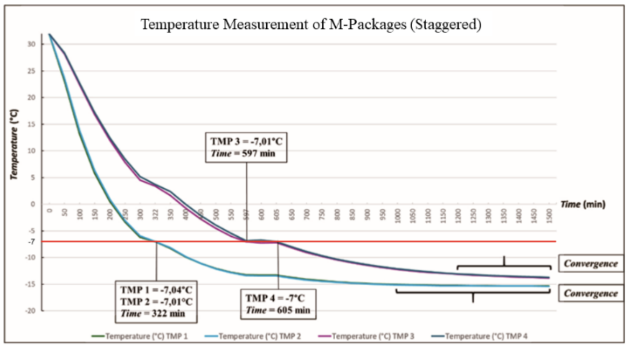
Tables 5 present a visual representation of the heat distribution in the two evaporator fin arrangement models once convergence has been reached. The analysis demonstrates that the staggered fin exhibits superior heat absorption efficiency in comparison to the inlined fin. The staggered fin is subjected to a greater heat load due to the higher absorbed temperature, enabling it to reach a lower temperature in comparison to the inlined fin.

B. *Phase 2*

Methods of model validation are employed: measurements using M-Packages, which are used to ascertain the time required for cooling; and M-Packages with an initial temperature of 32 °C, which are cooled to a temperature of -7 °C. The two freezer rooms are initially maintained at a temperature of 32°C and are equipped with evaporators utilising inlined and staggered fin arrays. The temperature input from the first phase simulation (point C) was used to cool both chambers, which were then simulated for a specified period of time until the temperature on the M-Packages components reached -7°C. The temperature of the M-Packages with an inlined fin arrangement was observed to reach -7°C after approximately 740 minutes (or 12.300 hours), while the staggered fin arrangement reached this temperature after approximately 605 minutes (or 10.080 hours).



(a)



(b)

Fig. 10. The following graph illustrates the temperature measurement of m-packages. a) inlined arrangement b) staggered arrangement

The temperature analysis in the freezer room has been completed. The subsequent step is to calculate the energy consumption required by the 2-door refrigerator product. The objective of this calculation is to ascertain the energy efficiency and specifications of the energy-saving sign label in accordance with the relevant regulatory requirements. Additionally, other research was conducted which addressed the potential for implementing modern energy-saving and energy-efficiency mechanisms. This was achieved by applying a comparative description of the practice of implementing energy service contracts and project and real estate certification systems in Russia and the European Union[27], [28], [29].

The objective of this study is to evaluate the electrical power consumption of refrigerators and determine the energy label in accordance with the international standard IEC 6225-2: 2015. The analysis was conducted through the measurement of the compartment volume in accordance with the specified temperature and the subsequent calculation of the actual energy consumption. In other research, the difference in energy consumption in freezers with open and closed doors is examined, resulting in a 40% greater energy consumption in open doors. This is not directly comparable to the methodology employed in the present study. However, the energy consumption measurement pattern can be used as a reference that is still related [22], [30].

The measurement of compartment volume is undertaken in order to adjust the target temperature of the refrigerator compartment. The aforementioned volume is adjusted by means of a correction factor that takes into account the temperature differential between the surrounding environment and the refrigerator compartment. This analysis facilitates the determination of the effective volume that can be employed to assess the energy efficiency of the refrigerator.

Table 6 presents the results of the volume adjustment calculation for the freezer and refrigerator:

TABLE 6. TABLE OF TOTAL VOLUME ADJUSTMENT

Compartement	Volume Adjustment (L)
Freezer	74.980
Refrigerator	130
Total	214.980

A calculation of the maximum energy consumption limit for a refrigerator with two doors is presented in order to determine the energy efficiency star level. In this context, lower values indicate a higher level of efficiency.The findings of the analysis demonstrate that the utilization of a 'staggered' configuration of evaporator fins in the refrigerator achieves the 1-star energy label standard, indicating that the device exhibits enhanced efficiency compared to the 'inline' model. Table 7 presents the results of the energy label analysis based on daily power consumption:

TABLE 7. TABLE OF ENERGY LABEL

No.	Fin Evaporator	Daily Power Consumption (Kwh/Day)	Energy Label
1	Inlined	1.230	0
2	Staggered	1.008	*

As evidenced by the preceding table 7, the utilization of staggered fin evaporators has been demonstrated to result in a reduction in energy consumption, thereby meeting the requisite energy efficiency standards. This illustrates the significance of an efficient design in reducing power consumption and enhancing the energy efficiency of refrigerators. Other studies have demonstrated the efficacy of CFD in establishing correlations and defining thermal parameters that can be employed to refine both simplified and comprehensive food storage models [31]. Additionally, CFD can be utilised for parametric analysis and optimisation.

Moreover, the study also calculated the running costs based on the daily power consumption. The discrepancy in energy consumption gave rise to a considerable divergence in running costs between the two types of evaporators. The utilization of staggered fin evaporators not only results in energy savings but also a notable reduction in running costs

CFD Simulation	**The configuration of the evaporator fin pipe arrangement**	
	Inlined	Staggered
Phase 1		
Average temperature of the region situated behind the blower fan within the mechanical chamber	-12.700°C	-15.410°C
Average temperature of of the fin surface of the fin evaporator	-16.839°C	-16.112°C
Phase 2		
Cooling speed of the freezer room	740 minutes	605 minutes
Power consumption of the refrigerator	1.230 kWh/day	1.008 kWh/day

In the preceding research, which constituted a reference point for this study, a comparable pattern was identified in the investigation of savings and efficiency levels in refrigerator systems utilising the IEC 62552 measurement standard to ascertain savings ratings [32].

IV. CONCLUSION

The CFD simulation results between inlined and staggered fin evaporators allow for the following conclusions to be drawn:

Validation of the model for Phase 1 indicates that the mean temperature of the region situated behind the blower fan within the mechanical chamber, when a staggered fin evaporator pipe configuration is employed, is superior to that observed in the inlined configuration, which exhibited a temperature of -12.700°C. Consequently, the CFD simulation for the temperature of the aforementioned region is deemed to have been successful in Phase 1.

The model validation for phase 1 revealed that the staggered pipe arrangement fin evaporator exhibited a superior heat absorption capacity in the mechanical chamber area, with a temperature of -16.110°C, in comparison to the inlined fin evaporator, which demonstrated a temperature of -16.830°C. Consequently, the CFD simulation for the temperature of the fin surface of the fin evaporator in phase 1 was deemed successful.

The results of the model validation for phase 2 demonstrated that the cooling speed of the freezer room using the staggered pipe arrangement fin evaporator was faster than that of the inlined arrangement, with a duration of 605 minutes compared to 740 minutes, respectively. Consequently, the CFD simulation for the cooling speed of the freezer room was deemed successful in phase 2.

The results of the model validation for phase 2 demonstrated that the power consumption of the refrigerator utilizing the fin evaporator staggered pipe arrangement was 1.008 kWh/day, which was more efficient than the inlined arrangement, which consumed 1.230 kWh/day. Consequently, the CFD simulation for calculating the power consumption of the refrigerator was deemed successful in phase 2.

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