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Experimental analysis of hybrid household refrigerators including thermoelectric and vapour compression cooling systems

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ABSTRACT

Two different hybrid refrigerators which include vapour compression and thermoelectric (TE) cooling technologies were built and tested. Serial refrigerators, which use vapour compression only were first tested to collect reference data for comparisons. Then, the hybrid prototypes were constructed by attaching thermoelectric coolers (TECs) to different compartments of these serial units. Among the chill, fresh food and freezer compartments of the refrigerators, the TECs were only used at chill and fresh food compartments, which have different cooling power requirements. Energy consumption, cooling and freezing capacity, and noise tests were conducted in compliance with three different standards.

All hybrid refrigerators operated successfully in various ambient temperatures and loading conditions. The test results showed that the hybrid refrigerators had at least three times higher energy consumption levels over those of serial ones, because of the lower operating efficiencies of the TECs and higher transmission losses. Moreover, their noise levels are extremely high, at least 25 dB(A) higher than those of serial ones. However, the TECs provided a more sensitive temperature control in the compartment in which they were used. Additionally, the hybrid refrigerators' performance in terms of cooling capacity was very promising. They were able to cool 17.5 kg of loads from an ambient temperature of 25 °C to the desired temperatures faster than the original serial refrigerators. Since the freezer compartments of both the serial and hybrid units are cooled by compressor-based cooling systems, the freezing capacity results were identical.

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Analyse expérimentale des réfrigérateurs domestiques hybrides intégrant des systèmes de refroidissement thermoélectriques et à compression de vapeur

Mots-clés: Refroidissement; Consommation énergétique; Niveau de bruit; Peltier; Réfrigérateur; Refroidisseur thermoélectrique; Compression de vapeur

1. Introduction

In 2016, 197 countries committed to reduce their usage of hydrofluorocarbons (HFCs) by 2019 in an amendment to the Montreal Protocol (Wahlen, 2016). This new global agreement on climate change was made by more than 1000 delegates representing different countries and organisations in the 28th meeting of Parties to the Montreal Protocol in Kigali, Rwanda. The aim was to phase out HFC refrigerants used in air conditioners and refrigerators to mitigate greenhouse gases that contribute towards climate change.

Compressor based vapour compression technology, which has a higher coefficient of performance (COP) and lower cost in comparison with its alternative technologies, has the highest share of usage in domestic refrigerators. In this technology, a refrigerant gas is used as coolant. The most widely used refrigerants are R134a and R600a. R134a is an HFC refrigerant that needs to be phased out as mentioned above. On the other hand, R600a is a natural refrigerant, a hydrocarbon (HC) and getting more attention due to its low

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Nomenclature

Abbreviations

CC	chill compartment
Com	compressor
COP	coefficient of performance (W W^{-1})
CRTR	compressor run time ratio (%)
DC	direct current (A)
EEC	energy efficiency class
EN	European norm
FC	freezer compartment
FFC	fresh food compartment
GWP	global warming potential
HC	hydrocarbon
HFC	hydrofluorocarbon
ICN	Institute of Child Nutrition
ICRT	International Consumer Research Testing
IEC	International Electrotechnical Commission
ODP	ozone depletion potential
RTR	run time ratio (%)
SLHX	suction line heat exchanger
TE	thermoelectric
TEC	thermoelectric cooler

Symbols

A	area (m^2)
c_{pack}	specific heat of the packages (kJ kg^{-1} $°C^{-1}$)
I	electric current (A)
k	heat conduction coefficient (W m^{-1} $°C^{-1}$)
L	thickness (m)
m	mass (kg)
Q	electrical power (W)
Q_A	active heat load (W)
$Q_{A,TEC}$	thermoelectric cooler active heat load (W)
Q_C	cooling effect (W)
$Q_{C,TEC}$	thermoelectric cooler cooling effect (W)
Q_H	heating effect (W)
$Q_{H,TEC}$	thermoelectric cooler heating effect (W)
Q_P	passive heat load (W)
Q_T	total heat load (W)
T_{cc}	target temperature of chill compartment (°C)
ΔT	temperature difference (°C)
UA	overall transmission losses (W $°C^{-1}$)
V	voltage (V)
X_s	the mass fraction of the solids in the food (%)

global warming potential (GWP) and the ozone depleting potential (ODP) of zero. It is used in more than 700 million household refrigerators worldwide, and it is estimated that by 2020 that R600a will have a 75% share of global production (Secop, 2016). However, it has a drawback of being flammable; hence it faces with some restrictions in use.

In addition to using a refrigerant, one of the disadvantages of vapour compression systems is that it is difficult to control the temperature of the target compartment when a single speed compressor is used in the system. Only the vapour compression systems equipped with variable speed compressors and electronic expansion valves are capable of precise temperature control. The temperature control is especially important for preserving food products which are sensitive to frequent temperature changes.

Due to the aforementioned drawbacks of vapour compression, a great deal of effort has recently been given to alternative cooling technologies. Thermoelectric/Peltier (TE) cooling is one of those alternatives and it is studied in this work because it is compact and has fewer moving parts. More importantly, there is no refrigerant used. The technology is simply based on the principle of Peltier effect that "*the passage of an electric current through the junction between two dissimilar conductors in a certain direction produces a cooling effect*" (Goldsmid, 1964). Moreover, it is also possible to control the inner temperature of target compartment with a higher degree of accuracy. However, thermoelectric coolers (TECs) have lower COP values and higher costs. Although there are no moving parts in its core system, fans can be installed on the heat sinks in order to increase heat transfer over its surfaces. This can cause high noise levels.

Thermoelectric (TE) cooling has been studied extensively since the introduction of semiconductors in the 1950s (Goldsmid, 2010) which led to the development of more efficient TECs. The studies up to now focused on design optimisation, performance improvement, and its materials. TE cooling and its comparison with other cooling technologies have also been investigated (Hermes & Barbosa, 2012; Bansal & Martin, 2000). Hermes & Barbosa (2012) compared the thermodynamic performance of the portable coolers that employ thermoelectric, Stirling, and vapour compression cooling systems. In their study, the Stirling and the reciprocating vapour compression refrigeration systems presented overall thermodynamic efficiencies of around 14%, whereas the TEC presented approximately 1%. A similar study was conducted by Bansal & Martin (2000) that investigated the performance characteristics of three domestic refrigerators, namely the vapour compression, the TE and the absorption refrigeration. Their study found that the vapour compression refrigerator had the highest COP (2.59) followed by the TE (0.69) and the absorption refrigerator (0.47), respectively.

Besides, significant efforts have been given to the application of thermoelectric cooling technology to the different cooling systems. The technology has a potential to meet the refrigeration demands in aerospace applications and low temperature applications by means of transverse Peltier coolers. One of the most popular applications of the technology is electronic cooling due to its compact size, low mass and vibration-free operation. Space and automotive air-conditioning systems are another potential field of application for thermoelectric cooling cited by the researchers.

The application of this technology to the household refrigerators has also attracted the researchers' attention (Vian & Astrain, 2009a,b; Astrain et al., 2012, 2016; Martinez et al., 2013; Riffat et al., 2001; Jugsujinda et al., 2011; Min & Rowe, 2006).

The authors focused on thermal analysis of the TECs' influence on the refrigerator performance. Similar experimental works to apply thermoelectric cooling technology to household refrigerators have already been carried out (Vian & Astrain, 2009a; Astrain et al., 2012). Those works concentrated on the electric power consumption and efficiency of hybrid refrigerators combining thermoelectric and compressor-based cooling systems. Development and validation of a computational model for the simulation of the complete hybrid refrigerator was another focus in their study. Astrain et al. (2016) investigated the effect of different heat exchange systems (water-air heat exchanger, finned heat sink, and heat pipes) on the efficiency of thermoelectric refrigerator. Their study showed that the higher COP values for TE refrigerators can be achieved through the optimal design of the heat exchangers. Vian & Astrain (2009b) developed a domestic refrigerator, without moving parts, with only the fresh food compartment cooled by TECs. To increase heat transfer a thermosyphon with two-phase and capillary lift design was applied on the cold side of TEC, whereas another thermosyphon, with two-phase and without fan was applied to the hot side of TEC. The experimental results presented that the compressor based refrigerator had half the electric power consumption of the TE refrigerator. In another work, Martinez et al. (2013) studied experimentally the influence of different temperature control systems on the electric power consumption and COP of a TEC. Systems studied included: an on/off controller, a

proportional-integral-derivative controller, and a novel operating system based on idling voltages. Their study proved that the controller based on idling voltages decreases the electric power consumption of the refrigerator by 32% and increases the COP by 64%, compared with the on/off controller. Riffat et al. (2001) investigated the application of heat pipes and phase change materials for TE refrigeration. They designed and constructed two different TE refrigerators: the first one employed a conventional heat sink system (bonded fin heat sink) on the cold side of TEC. The other had an encapsulated phase change material in place of the conventional heat sink. Both refrigerators employed heat pipe embedded fins as the heat sink on the hot side. In their study, it was found that application of encapsulated phase change material improved the performance of TE refrigerator. Jugsujinda et al. (2011) analyzed a TE refrigerator performance. The study showed that the TE refrigerator's maximum COP was 0.65 W^{-1}. Min & Rowe (2006) developed prototypes TE domestic refrigerator and they evaluated them regarding the COP, heat-pumping capacity and cooling-down rate. They found that the COP of a TE refrigerator was around 0.3–0.5 W^{-1} for the operating temperature of 5 °C with ambient temperature at 25 °C.

This study has differences in terms of the investigation of thermoelectric cooler application to household refrigerators and its performance analysis considering (1) different ambient temperatures (2) operating conditions (3) loading conditions. Different types of tests were carried out to comply with different standards to measure its performance in various conditions. As will be discussed in the following sections, even though energy consumption is of prime importance to the measurement of refrigerator's performance, there are other key aspects such as cooling and freezing capacity, and noise level which have direct effect on the satisfaction of end-users.

The originality of this work can be summarised as follows:

- The current work includes a whole, key performance analysis of the hybrid household refrigerators to gain a complete understanding of them. The authors did not find any prior experimental work on the same test unit addressing the different aspects of the type of refrigerators studied here.
- The tests in this study were performed according to valid household test standards EN 62552:2013 (EN-62552:2013, 2013), new IEC 62552:2015 (IEC-62552:2015, 2015), IC 15068 (ICRT, 2015), and IEC 60704-2-14 (IEC-60704-2-14, 2014). Experimental studies involving these three standards were not found in the literature.
- This work experimentally proved that despite the higher energy consumptions observed, rapid cooling can be achieved by implementing thermoelectric coolers.

2. Objectives of the study

The principal objectives of this experimental study were:

- To build a hybrid household refrigerator like the one explained by Vian & Astrain (2009a), combining both vapour compression and thermoelectric cooling technologies.
- To measure the influence of the TECs applied not only to chill but also the fresh food compartment, which has different cooling power requirements due to the different target temperatures and volumes of the respective compartments.
- To understand the effect of current commercial TECs on the performance of household refrigerators in terms of energy consumption, cooling and freezing capacity, and noise tests.
- To concentrate on the benefits of TECs so as to provide opportunities for the application of thermoelectric cooling technologies.



Fig. 1. Serial refrigerator.

Table 1
Specifications of the analysed serial refrigerators.

Specifications	Units	Declaration values
Charge	g	46.0
Fresh food net volume	l	175.0
Chill net volume	l	81.0
Freezer net volume	l	87.0
Total net volume	l	342.0
Energy consumption, daily	$kWhd^{-1}$	0.492
EEC	–	A+++
Climate classes	–	SN-T
Noise level	dB(A)	38

- To provide reference outputs for further works and optimisation studies.
- To provide reference test data to verify Computational Fluid Dynamics (CFD) analysis results for optimisation purposes.

3. Experimental setup

3.1. Specifications of serial refrigerators

The serial refrigerator, KGN39 premium produced by Bosch, is a bottom freezer type with two doors and the following three compartments (see Fig. 1): *fresh food compartment (FFC), chill compartment (CC) and freezer compartment (FC)*. Its specifications are shown in Table 1. FFC and CC are separated from each other by a division plate. This refrigerator contains a vapour compression cooling system presented in Fig. 2. It has a single cooling circuit including a variable speed compressor, an air-cooled evaporator and two skin condensers in the side walls. The warm air is first cooled in the evaporator then, cooled air is pumped by a fan to the compartment by means of air channels. All compartments have their own thermostats to maintain inner temperatures at desired levels. Due to this operation mode, there is no simultaneous cooling of the compartments. On the other hand, the hybrid prototypes developed in the references Vian & Astrain (2009a) and Astrain et al., (2012), were based on the model of Bosch KGP39331.

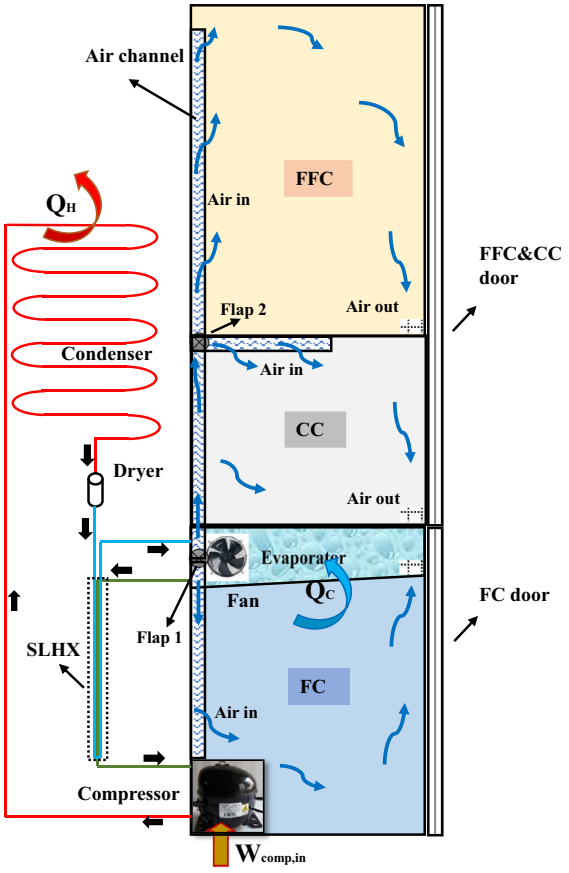

Fig. 2. Schematic diagram of the vapour cooling system of the analysed serial refrigerator.

It has two compartments, fridge and freezer, and two compressors which enable independent cooling of the compartments. The two-compressor based system has a potential of being more efficient and having higher cooling and freezing capacity than the one-compressor system. However, more space is required for the compressors, system complexity is increased and maintenance costs may go up. Finally, it may increase the noise level.

In order to collect reference testing data, two non-modified serial refrigerators named, Serial I and Serial II, were examined beforehand. Their test results were compared with each other for validation purposes.

The target temperatures of the compartments will be presented in the following sections. These targets can change depending on the standards, test specifications and the type of tests. In this study, EN 62552:2013 (EN-62552:2013, 2013), Household refrigerating appliances – Characteristics and test methods, forthcoming IEC 62552:2015 (IEC-62552:2015, 2015) and finally consumer magazines (ICRT) test programme of IC 15068 (ICRT, 2015) were considered.

3.2. Thermoelectric coolers

In this work, a commercial TEC manufactured by Marlow was chosen according to the heat load requirements of the compartments in where it was located. The heat load requirements' calculations are based on the measurements of overall transmission losses and the calculations stated in the following subsections of 3.2.1 and 3.2.2, respectively.

The properties of the TEC are shown in Table 2. The cooling technology is based on the system represented schematically in Fig. 3. In the core of the system, there are P and N semiconductors, connected with each other electrically in series and thermally in parallel, which are sandwiched between the ceramic materials. In order to increase heat transfer between the faces of the TEC and air, the heat dissipaters comprised of aluminum fins and fans are attached to the ceramics. Basically, on both faces of the TEC, air is withdrawn by the fans, moves through the fins and finally leaves the cooler. On the cold face, the cabinet air gets colder while ambient air gets warmer on the hot face.

Table 2
Thermoelectric coolers applied to prototypes.

Model	CTA305 (TEC)
Capacity [W]	143
Heat transfer	Air to air
Voltage [V]	DC, 24V
Current [A]	7.5
External fan rating [dB(A)]	51

Table 3
UA results.

Models	FFC W/°C	CC W/°C	FC W/°C
Serial I	0.648	0.449	0.378
Serial II	0.654	0.441	0.368
Hybrid I	0.771	0.495	0.376
Hybrid II	0.710	0.482	0.370

3.2.1. Overall transmission losses of the cabinets

The overall transmission losses (thermal conductance) of the serial and hybrid prototype refrigerators, (kA)/L, which will be referred to as UA [W/°C] (Here U stands for k/L) were measured (Eq. (1)). Here, a controllable heat flow rate is supplied by a heating resistor of 30 W which is located inside the compartment. A constant ambient temperature of 16 °C is provided in the test chamber during the whole measurement. The heaters increase the interior temperatures of the compartments and keep it around 40 °C. After reaching stabilization, the test stops. The electrical power supplied by the heating resistor is measured as well as the temperature difference between the inner temperature of the compartments and ambient temperature. Then, the UA value is calculated using Eq. (1).

$$UA = (kA)/L = Q/\Delta T \qquad [W^{\circ}C^{-1}] \tag{1}$$

Experimental measurement is the most practical and effective method for calculating these transmission losses. This not only enabled the authors to choose suitable thermoelectric coolers in terms of cooling power but also helped us understand heat loss through the walls and effect of insulation on the energy consumption.

The measured UA results of each model are shown below Table 3.

The results show that the transmission losses through the walls of serial units' compartments are in close alignment; the differences are under 3%.

Compared to Serial I, the UA of Hybrid I's FFC and CC are higher by 18.9% and 10.2%, respectively. Similarly, the UA of Hybrid II's FFC and CC are higher than those of Serial II by 8.5% and 9.2%, respectively. Those results are expected because there are heat leakages through the locations on the hybrid refrigerators' walls where TECs are mounted. The higher transmission losses of the prototypes surely lead to higher energy consumption.

3.2.2. Heat load calculations

For the purpose of selecting the most suitable TEC, the basic passive and active heat loads were calculated for FFC and CC

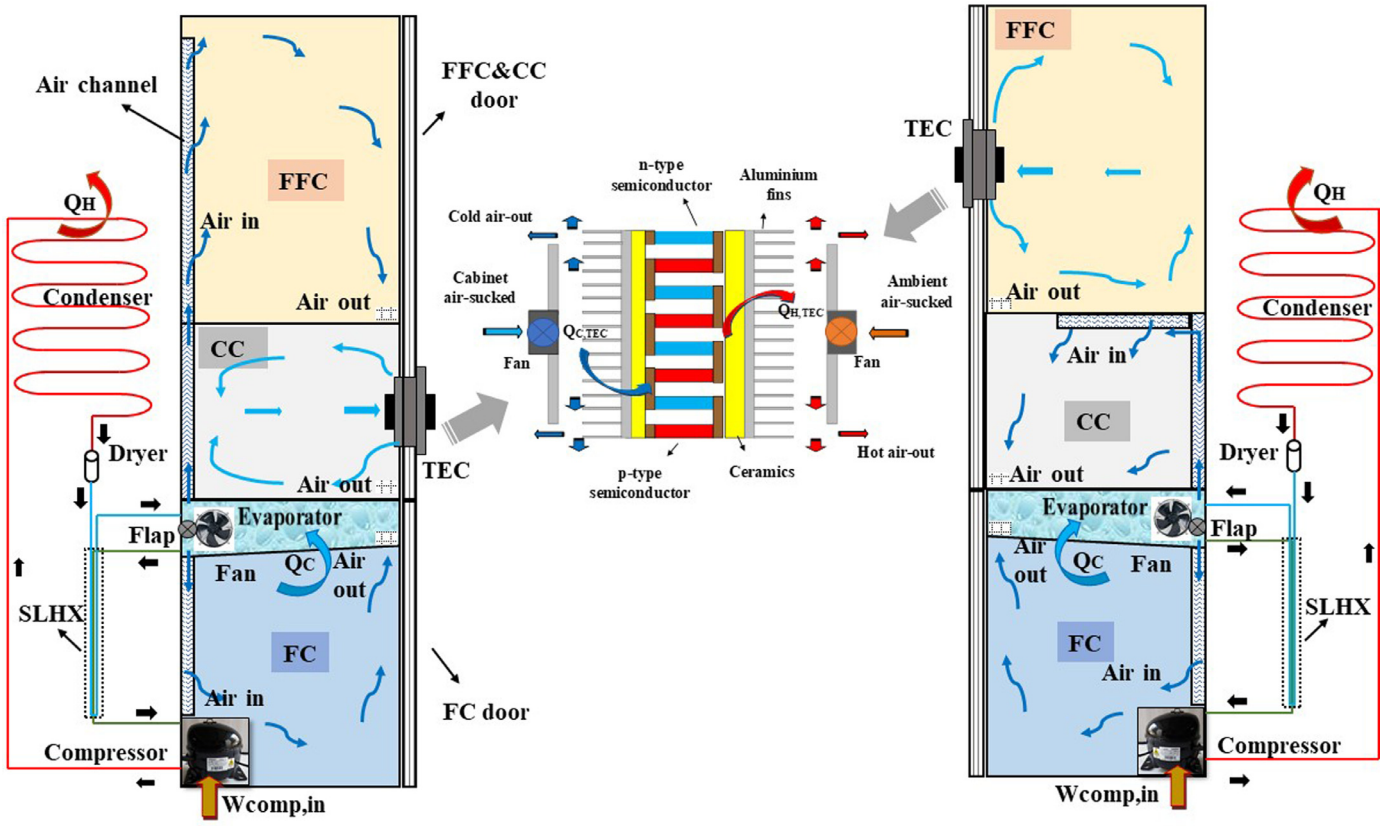

Fig. 3. Schematic representation of the hybrid refrigerators (Hybrid I and Hybrid II, left to right).

in consideration of various scenarios because the tests were performed at different room temperatures (ranging from 16 to 32 °C) at different loading conditions. TEC was determined taking into account of the maximum heat load conditions.

Passive heat loads (Q_P) are formed by the heat transfers through the compartments' wall and door gaskets (transmission losses). After measuring UA as explained in Section 3.2.1., it is calculated by taking into account the differences between the ambient and compartment temperatures (Eq. (2)).

$$Q_p = UA\Delta T \quad [W] \tag{2}$$

Active heat loads (Q_A) arised from (1) Heat transfer through TEC, $Q_{A,TEC}$ (some of the heat produced by the Peltier moves into the compartment). It was provided by the manufacturer and its value was about 50% of passive heat load. (2) Inserting food into the compartments (because test packages (Tylose packs) were used in the tests rather than food, the properties of Tylose packs' were used in the calculations). Total active heat loads are calculated as presented in Eq. (3).

$$Q_A = Q_{A,TEC} + mc_{pack}\Delta T \quad [W] \tag{3}$$

In where, c_{pack} is the specific heat of the package. For an unfrozen food, it is calculated by Eq. (4) (Chen, 1985):

$$c_{pack} = 4.19 - 2.30Xs - 0.628Xs^3 \quad [kJkg^{-1}{}^{\circ}C^{-1}] \tag{4}$$

In where, Xs: the mass fraction of the solids in the food (= 23.6% for the packs).

Total heat loads (Q_t) are the sum of all passive and active loads and simply shown in Eq. (5).

$$Q_T = Q_P + Q_A \quad [W] \tag{5}$$

The maximum heat load conditions occur when warm foods are inserted into the compartments. This condition can be simulated by cooling capacity test performed at the ambient temperature of 25 °C mentioned in Section 5.4. As a result of calculations, the total heat loads of FFC and CC were roughly 45 W and 21 W, respectively.

3.3. Hybrid household refrigerators

Within this study, the term "hybrid refrigerator" refers to the refrigerator in which both vapour compression and thermoelectric cooling systems were implemented. They can refrigerate separate compartments at the same time thanks to their independent operation from each other. This brings extra flexibility in use. Here, when a TEC is applied for a compartment, the air channel openings in that compartment were sealed to eliminate the vapour compression cooling effect.

Two prototype hybrid refrigerators, in Figs. 3 and 4, were built after the modification of serial refrigerators (Serial I and II). Hybrid I was created by modifying Serial I. TEC was used for the cooling of CC in this prototype. On the other hand, Hybrid II was created by modification of Serial II. Here, TEC is used for cooling the FFC.

3.3.1. Hybrid I

To build this refrigerator, Serial I's body was used. The TEC was mounted into the door of Serial I (Figure 4) to chill CC.

3.3.2. Hybrid II

The TEC was applied to the Serial II to build this hybrid refrigerator. The purpose was to cool the FFC which makes this prototype different than the former one. The TEC was placed in the door of Serial II and the heat released into the environment (Fig. 4).

In the hybrid refrigerators, TECs were attached to the doors because,



Fig. 4. Hybrid I and Hybrid II (left to right).

- The intention was not to damage the main body of the original serial refrigerators in case of multiple tests. If the body is modified, hybrid refrigerator can no longer be converted to the serial refrigerator. But if the door is modified, it is enough to replace the modified doors with a door that hasn't been modified.
- There were skin condensers on the side walls and air channels in the rear of the serial refrigerators which prevented TECs being placed in these regions.

These two prototypes helped the authors evaluate the performance and effect of TECs in various ways such as (a) application in different compartments which have different volumes and cooling capacity needs and (b) its behavior against different ambient temperatures.

In the work of Vian & Astrain (2009a) following the computational analysis, it was decided to establish the hybrid refrigerator in which TEC's heat was released into the FFC rather than the ambient to increase TEC's efficiency. This was done because the lower the temperature difference between the TEC's faces, the higher the COP of TEC. Yet, in this current work, the configuration chosen by them was not preferred, because:

* To investigate TEC performance under real ambient temperatures (household refrigerators usually operate in the room temperatures between 16 and 32 °C).
* In spite of being a more appropriate configuration from the energy point of view, its cooling capacity performance would most likely be poor because warm foodstuffs added into the FFC will cool down slower due to the heat released by the TEC.

4. Description of the experimental procedures

4.1. Standards, specifications and tests

Several tests were carried out complying with three different standards/test specifications. They are summarised in Table 4.

Table 4
Standards, specifications and the tests.

Tests	EN 62552: 2013	IEC 62552: 2015	IC 15068	IEC 60704-2-14
Energy consumption	●	●		
Cooling capacity		●	●	
Freezing capacity	●	●	●	
Noise				●

4.2. Test procedures

The tests of two serial refrigerators were initially performed to collect valid reference data.

After concluding Serial I's tests, the Hybrid I was built on the Serial I's body. The same tests were also performed with the Serial II. Following the tests, the Hybrid II was built on the same body of Serial II.

Building the hybrid refrigerators on the same body of the serial units was very workable for a reliable comparison of the test results. This enabled us to measure only the effect of the cooling technologies (vapour compression and TE) on the performance of the refrigerators; because, it lessened the variables such as insulation quality of the walls and heat transfer through the gaskets which directly affect the cooling performance of the refrigerators.

4.3. Test chamber

The tests were carried out in the climate chambers located at the R&D Cooling Center of BSH Bosch Household Appliances in Çerkezköy, Tekirdağ, Turkey. The humidity and temperature inside the chambers can be set as required. The humidity was kept between 35 and 50% during the tests. The temperature inside the chamber ranges between 10 and 43 °C.

It is possible to collect test data of temperature, pressure, mass flow and power at each test station inside the chambers. Test data are collected by means of data acquisition systems and then transmitted to the test software to analyze the results.

4.4. Measurement instruments

During the tests, the power is measured with a basic accuracy of 0.025% by Zimmer LMG500 power meter. Daily energy con-

Table 5
Compartment target temperatures and loading conditions for energy consumption tests.

Standard	Ambient	FFC		CC		FC	
	(°C)	*Target temp.*(°C)	*Measured by*	*Target temp.*(°C)	*Measured by*	*Target temp.*(°C)	*Measured by*
EN 62552:2013	25.0 ± 0.5	≤ + 5.0	Cu cylinder	−3.0 ≤ Tcc ≤ + 3.0	Packages	≤ −18.0	Packages
IEC 62552:2015	16.0 ± 0.5 and 32.0 ± 0.5	≤ + 4.0	Cu cylinder	≤ + 2.0	Cu cylinder	≤ −18.0	Cu cylinder

sumptions were measured with an uncertainty of less than 2%. Relative humidity had an overall uncertainty of measurement of not greater than 5%. Calculated values of test duration, made up of the difference between time recorded at each sampling period, had an expanded uncertainty of 0.1%. T type calibrated thermocouples were used as temperature instruments with a measurement uncertainty of ± 0.2 °C. The test data were collected by the datalogger, Agilent 34970A.

For cooling and freezing capacity tests, the packages which consist of oxyethylmethylcellulose, sodium chloride and water, described in the given standards (EN-62552:2013, 2013; IEC-62552:2015, 2015), were used. The tolerances for the dimensions of packages were ± 2 mm for small packages, ± 3 mm for larger ones. The tolerances of masses of the packages were ± 2%.

Regarding the noise level measurements, the tests were performed in a semi-anechoic chamber-class 1 (ISO 3741) with the measurement sensitivity of 43.1 mV Pa^{-1} and the microphone uncertainty of 0.2 dB.

5. Results and discussion

5.1. Energy consumption

EN 62552:2013 and new IEC 62552:2015 standards are considered as reference norms for energy consumption tests because both norms have different measurement methods. Moreover, it is useful to know the energy consumption performance of the hybrid prototypes under different test conditions. While EN 62552:2013 is still in use in the EU, the forthcoming IEC 62552:2015 will be valid after 2020.

The target compartment temperatures and measurement methods are presented in Table 5. The critical differences between them are the ambient and the FFC target temperatures as well as the loading conditions of the freezer. The test packages are not used in IEC 62552:2015.

5.1.1. Energy consumption results according to EN62552:2013

The energy consumption test results are given in Fig. 5. Here, Serial II has lower energy consumption than Serial I although they have the same configurations. Serial II's consumption is 2.7% less than that of Serial I. However, those differences in the results are reasonable due to changes in the efficiency of the components, particularly the compressor COP of the cooling systems and insulation quality, etc.

It is also clear from the Fig. 5 that hybrid refrigerators have higher energy consumption levels than the serial ones. Hybrid I's energy consumption result at ambient temperatures of 25 °C is four times higher than those of Serial I. The same differences can be seen between the energy consumption of Serial II and Hybrid II.

5.1.2. Energy consumption results according to IEC62552:2015

The results are similar to those conducted according to EN 62552:2013. Fig. 6 reveals that the energy consumption level of Serial II is lower than Serial I; it has 5.4 and 7.5% lower energy consumption levels at 16 and 32 °C ambient temperatures, respectively.

The hybrid refrigerators have higher energy consumption compared to the serial ones. Hybrid I's energy consumption at an ambient temperature of 32 °C is four times higher than Serial I. On the other hand, at an ambient temperature of 16 °C, its consumption is three times higher than Serial I's consumption. This is because, at low ambient temperatures, thermoelectric coolers operate more efficiently. Similar differences can be seen between the energy consumption of Serial II and Hybrid II.

5.1.3. Root causes and key points for the higher energy consumptions of hybrid refrigerators

The root causes and key points for the higher energy consumption of hybrid refrigerators at an ambient temperature of 25 °C are discussed below (this is because the refrigerators' energy consumption at ambient temperatures of 16 and 32 °C has similar patterns with the one at 25 °C).

- *Lower COP values of TECs*: The TEC system COPs used in Hybrid I and II are up to 0.37 W^{-1} and 0.30 W^{-1} respectively. Those values are considerably lower compared to the vapour compression system COPs used in the serial units which are close to 1.8 W^{-1}.
- *Higher power consumption of TECs*: In Fig. 7, the power consumed for each compartment at the ambient temperature of 25 °C are presented. Hybrid II's FFC has the highest power consumption, just above 170 W; followed by Hybrid I's CC, 136 W. Those compartments were cooled by TECs, which need high power to provide target temperatures.
- *Run time ratio (RTR)*: Another crucial factor determining energy consumption level is run time of the compressor and TEC. It is the ratio of their operation time to the total analysing time. The longer these components run, the more energy that is consumed in the on/off operation. For instance, although Hybrid I has lower power consumption than Hybrid II as presented in Fig. 7, its daily energy consumption is still higher than that of Hybrid II. This is due to the higher run time ratios of TEC system of Hybrid I. The RTR values of different configurations for each compartment are displayed in Fig. 8, Hybrid I's RTR is 28% higher than Hybrid II.
- *Effect of insulation, UA*: Insulation of the compartments is the most critical parameter which affects energy consumption. Since there is a heat flow from the ambient to the inside of the compartments through the TECs, the insulation quality of the hybrid refrigerators is worse than the serial ones. According to the UA test results highlighted in Section 5.2, mounting the TEC on the serial refrigerators increases heat transfer by almost 10%. The TECs applied to the hybrid units have an on/off cycle, operated according to the compartment temperature sensor. Even when the TEC is off, there is a great deal of heat flow through them. The measures to evaluate insulation quality can be taken such as; (1) as proved by Martinez et al. (2013) the continuous run of TECs by supplying them with idling voltages instead of operating them by on-off temperature controllers could be more effective to eliminate heat flow through TECs, (2) the TECs can be located outside of the compartment, so the air cooled by the TEC can be transferred into the target compartment by air channels (3) the insulation material and dimensions of the walls can be changed to decrease heat transfer coefficients. All

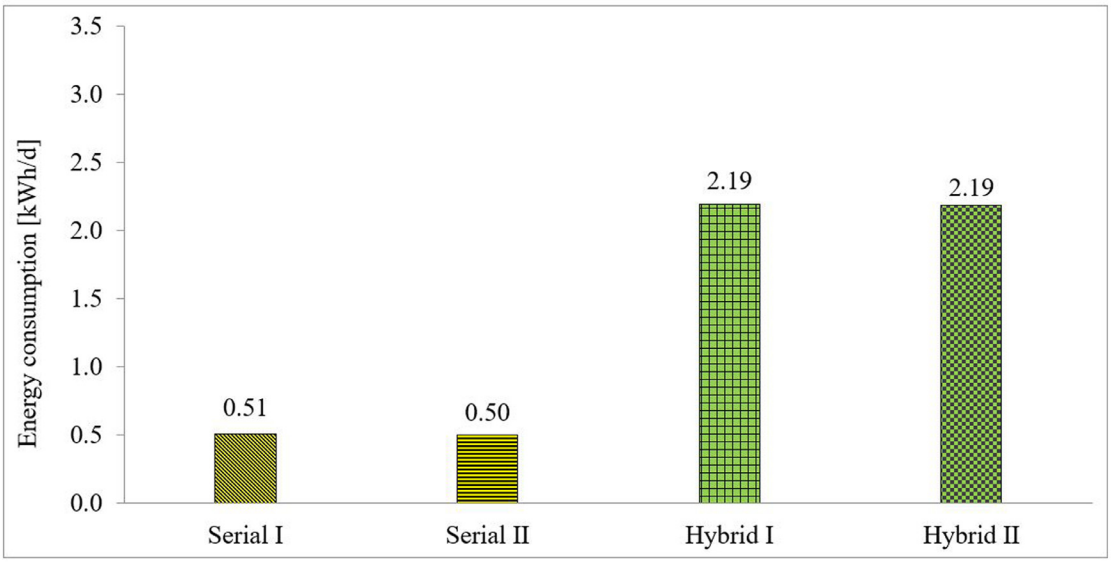

Fig. 5. Energy consumption test results according to EN62552:2013.

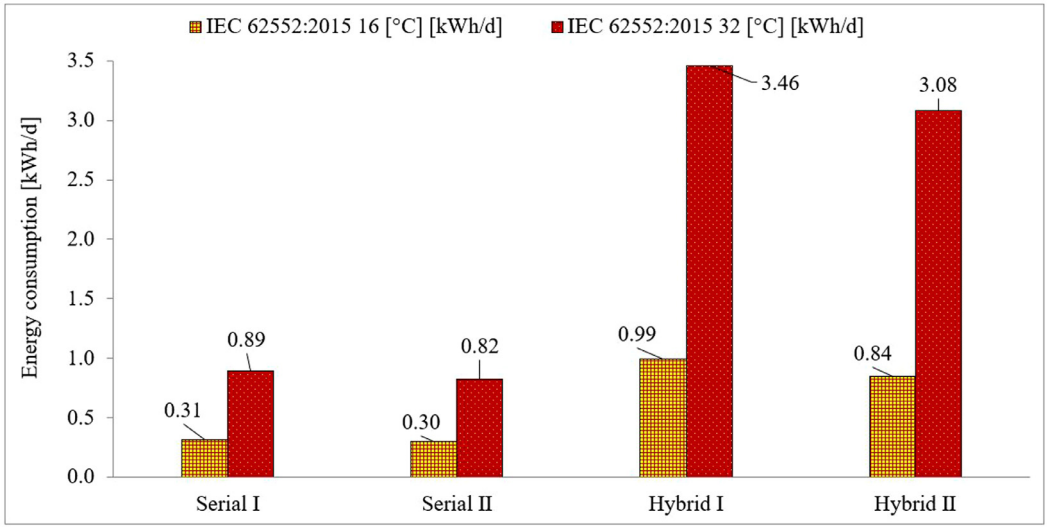

Fig. 6. Energy consumption test results according to IEC62552:2015.

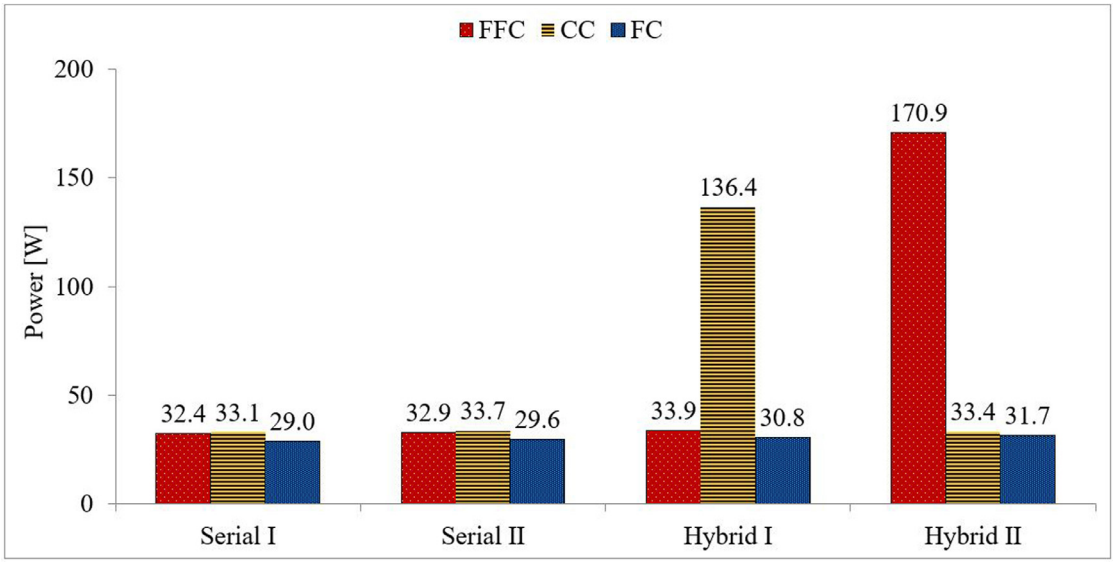

Fig. 7. Electrical power consumption (EN62552:2013).

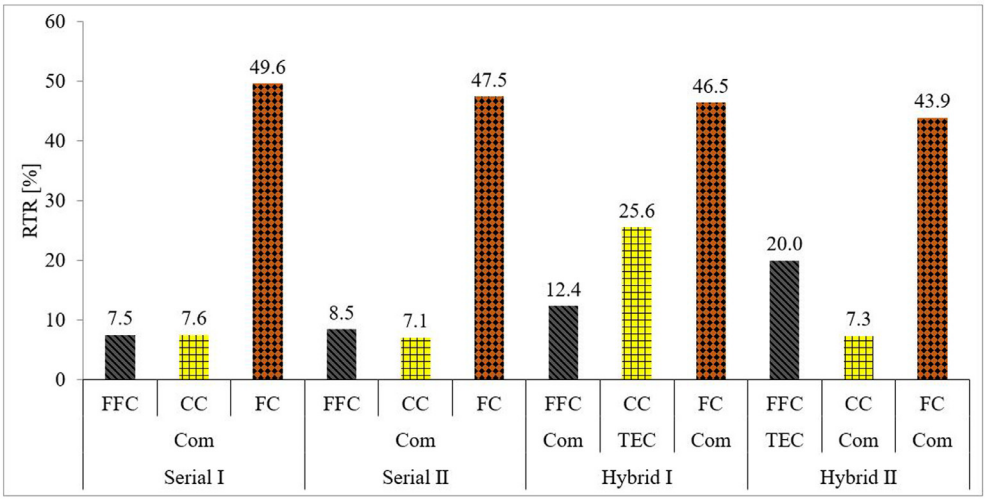

Fig. 8. Run time ratio of the refrigerators (EN62552:2013).

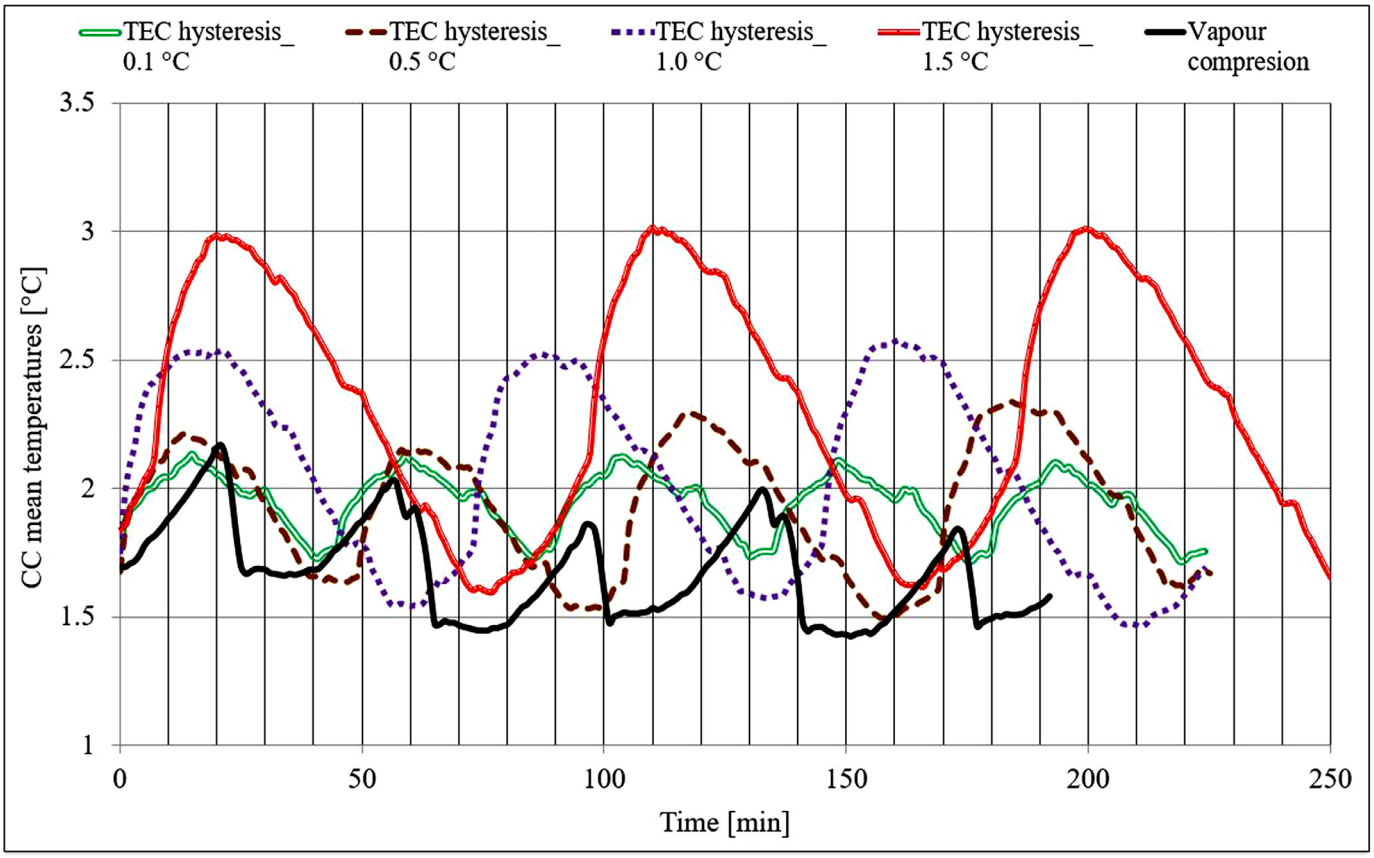

Fig. 9. Fluctuations in the average CC temperatures of Serial I and Hybrid II.

these measures need a significant amount of effort and will not be investigated within the scope of this study.

5.2. Temperature control with TECs

It is extremely important to control the interior temperature of the compartment where highly perishable foodstuffs are held. Examples of these foods are meat, poultry, fish, milk, eggs and cooked meals. The chill compartment is designed specifically for the purpose of preserving perishable foods.

In Fig. 9, fluctuations in the average chill temperatures of Serial I and Hybrid I are displayed (as mentioned in the previous sections, the CC of Hybrid I is cooled by TEC). The temperature data was collected from the energy consumption tests performed at an ambient temperature of 32 ± 0.5 °C. The temperature control settings were set to values to provide an average chill compartment temperature of just below 2.0 °C. The chill compartment temperatures were measured from the locations emphasized in IEC 62552: 2015 (*no packages were used*). The effect of TEC hysteresis on the Hybrid I's CC temperature behavior was studied.

According to Fig. 9, it is possible to control interior temperature of the chill compartment with high accuracy of ± 0.1°C if the TEC hysteresis is set to 0.1 °C. With the increasing hysteresis, the tem-

Table 6
Compartment target temperatures and loading conditions for cooling capacity tests.

Standard	Ambient	FFC		CC		FC	
	(°C)	*Target temp.*(°C)	*Measured by*	*Target temp.*(°C)	*Measured by*	*Target temp.*(°C)	*Measured by*
IEC 62552:2015	25.0 ± 0.5	≤ +4.0	Cu cylinder	−3.0 ≤ Tcc ≤ +3.0	Cu cylinder	≤ −18.0	Cu cylinder
IC 15068	25.0 ± 0.5	≤ +4.0	Packages	≤ +2.0	Packages	≤ −18.0	Packages

Table 7
The amount of test packages for cooling capacity test.

Standards	IEC 62552:2015			IC 15068		
Packages	*FFC*	*CC*	*FC*	*FFC*	*CC*	*FC*
Warm [kg]	7.5	–	–	17.5	8.0	–
Cold [kg]	–	–	–	10.5	5.0	21.0

perature stability inside the chill compartment worsens. Although it is more serviceable to decrease hysteresis for a sensitive temperature control, decreasing hysteresis leads to high energy consumptions. In the tests, the TECs' hysteresis was adjusted to 0.5 °C which was the optimum value in terms of temperature control and energy consumption. By increasing hysteresis from 0.1 to 0.5 °C, energy savings of approximately 5% were achieved. It should also be noted that at all hysteresis values of TEC, the cut-in and cut-off temperatures were kept at certain ranges which provides steadier temperature conditions inside the compartment.

Besides, the control on the Serial I's chill compartment temperatures is at acceptable level with an accuracy of ± 0.4 °C. However, it is difficult to control more sensitively due to the on/off run of the compressor and dependant on the operation between the compartments.

5.3. Cooling capacity

The cooling capacity test is the most critical test to measure cooling capability of the compartments which have a target temperature of above 0 °C. The fundamental purpose is to determine the time for a specified amount of load to be cooled from 25 to 10 °C (IEC-62552:2015, 2015).

The test was performed in regards to the IEC 62552:2015 norm and IC 15068 test specification. The EN 62552:2013 standard does not include this test. Table 6 demonstrates the compartment target temperatures and loading conditions for cooling capacity tests.

In IEC 62552–2015, the tested refrigerator is prepared for the cooling capacity test as it is done for the energy consumption test. The refrigerator is empty at first, that is, there are no cold packages inside the compartments (the temperature measurements are again made by Cu cylinders). It shall provide the target compartment temperatures and be in stable conditions before insertion of warm test packages. Before loading, the warm packages are kept at 25 °C ± 0.5 °C and then they are inserted into the FFC. If a super cooling function exists for the FFC, this should be activated immediately after loading.

The same procedure also applies for the IC 15068; however, all compartments should initially include cold packages. Before inserting the warm packages, the average temperature of the cold packages must be at or below the target compartment temperature. Additionally, the warm packages are loaded not only into the FFC but also CC. Finally, the test is performed twice with and without activation of super cooling function.

The authors preferred to use the naming used in the norm of IEC 62552:2015 for "cooling capacity". Normally, after the cooling time is determined, the capacity and the amount of load to be cooled, is calculated in kg. However, in this investigation, the results were analyzed in time required for cooling in minutes.

The amounts of warm and cold packages loaded into the compartments are shown in Table 7. As this table indicates, IC 15068's loading amounts and conditions are more challenging compared to those of IEC 62552:2015's.

Before the analyses, it must be noted that there are some critical factors which directly affect the cooling time test results. Those are: (1) the temperature of the warm packages and compartments at the moment of insertion, (2) loading time, (3) air humidity of the test chamber and (4) measurement errors. In each test, the temperature variation between the warm packages was kept at ± 0.1 C. The differences in average temperature of the warm packages in the tests are maintained at ± 0.5 °C. Additionally, the

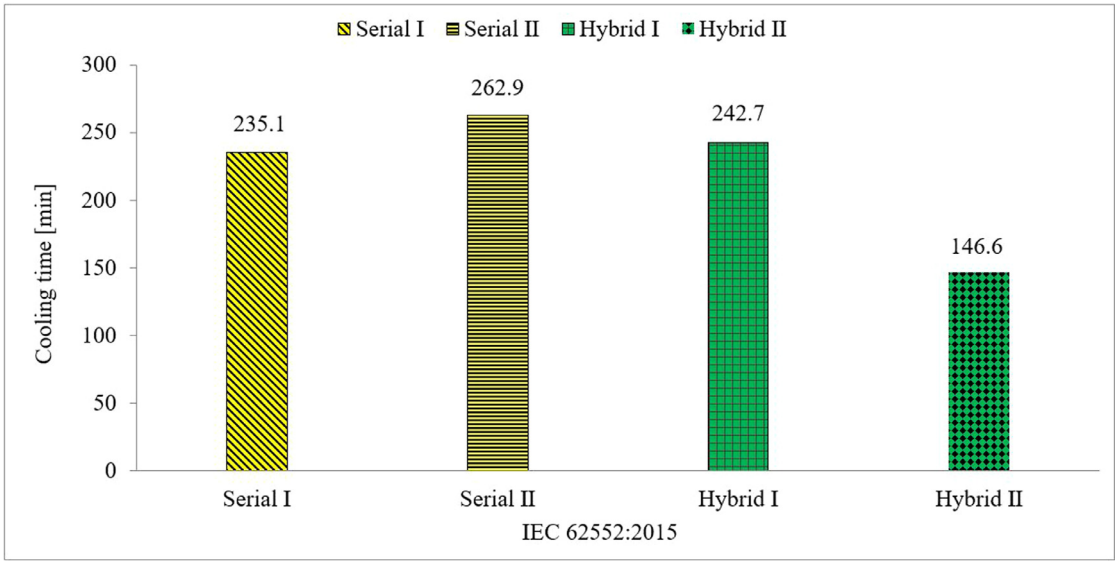

Fig. 10. Cooling capacity test results according to IEC 62552:2015.

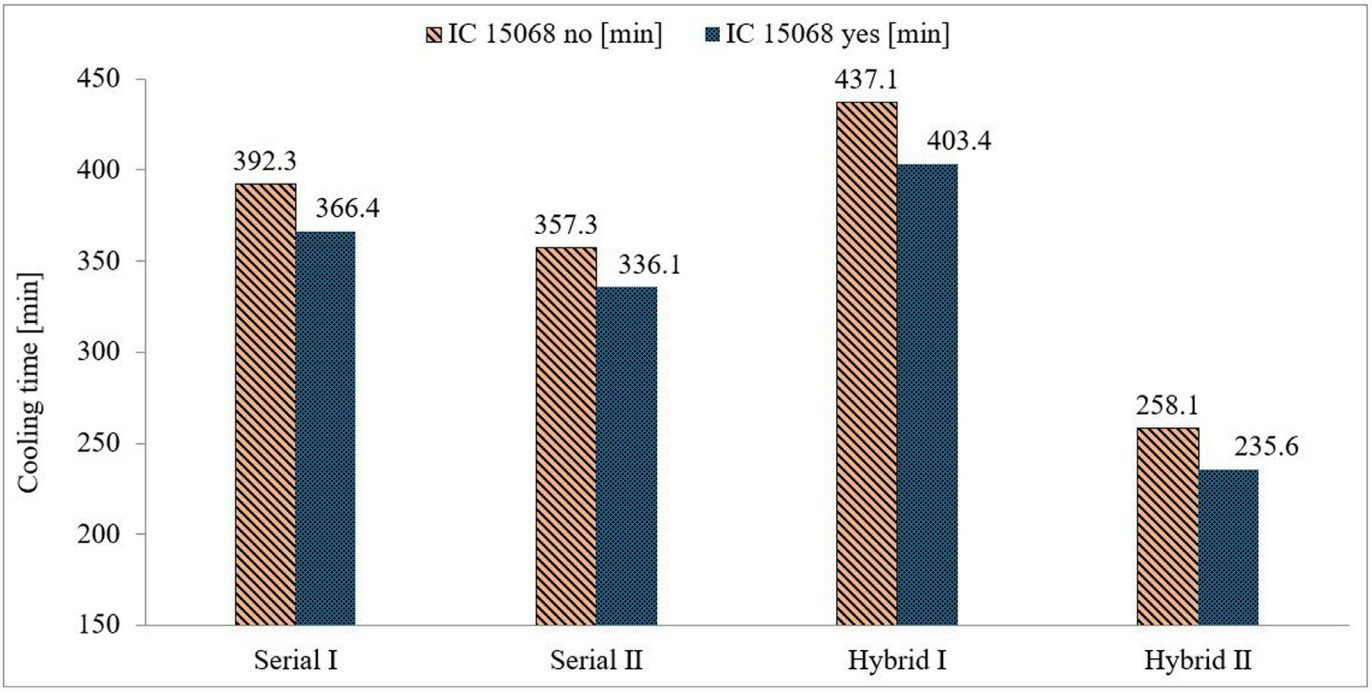

Fig. 11. Cooling capacity test results according to IC 15068.

allocated time for the loading was less than 90s. All those factors affect the accuracy of the results.

5.3.1. Results according to IEC 62552:2015

The results are presented in Fig. 10. The average cooling time of the serial refrigerators is approximately 250 min and the difference between them is roughly 10%. The difference is at an acceptable level; thus, the results of the serials can be considered as a reference. The Hybrid I refrigerator has very similar results to the serial ones. This is expected because Hybrid I's FFC is cooled by a compressor based system as in the serial ones. Hybrid II has the lowest cooling down time with a value of 146.6 min (2.44 h). This is a considerable achievement because the warm packages were cooled down in approximately 40% less time compared to the others.

5.3.2. Results according to IC 15068

Fig. 11 summarises the test results in compliance with IC 15068 for cases of super cooling activation (Yes) and without super activation (No). Serial refrigerators' cooling time measurements have a difference of 9.0 and 9.8%, with and without super activations, respectively. Those reference results are also relevant. Additionally, in the case of super activation, the cooling time is around 6% lower than the no super activation case. One could expect much lower cooling time values when the super cooling function is activated. Yet, there is a certain restriction about the average internal temperatures of the FFC which shall be kept between 0 and 8 °C. The temperature is not allowed to drop below 0 °C. This restriction must be carefully considered in the design of the super cooling process otherwise icing may occur in some regions of the FFC.

Hybrid I's performance is poor, cooling time levels are 10 to 17% higher than those of serial ones and 70% higher than the Hybrid II's. Hybrid I is in fact supposed to have less cooling time, since the CC is cooled by the TEC. The primary reason for this is the location of TEC, positioned to the front side of the CC. The CC has drawers that prevent cooled air to flow over the warm packages. As mentioned earlier, the CC of other refrigerators are cooled by a compressor-based system and air is blown into it from the top and directly flows over the packages.

Hybrid II has the best cooling performance; its cooling time is at least 32% lower than those of the serial ones. This is also a notable success. The leading factors are (1) as explained in the previous paragraph, direct air flow over the warm packages in the CC and (2) using separate cooling technology, TEC, for FFC. Since there is no drawer in the FFC, the cooled air passes through the warm packages accelerating the cooling process. It must be highlighted that 17.5 kg of warm packages were cooled in Hybrid II's FFC by TEC in less than 250 min.

5.3.3. Rapid cooling with TEC

The promising results of Hybrid II ought to be investigated in detail because it is possible to design a compartment that has a rapid cooling feature.

Rapid cooling, also called blast chilling, is strongly advised for protecting the nutritional values and freshness of the foodstuffs. This feature is therefore increasingly paid attention by the domestic refrigerator users. There is no common definition of rapid cooling in the norms but a small number of food agencies which describe it and define its criteria (Dixon & Hall-Campell, 2016; FSA, 2016). In the report of Dixon & Hall-Campell (2016), it is pointed out that hot food must be cooled from 57.2 to 21.1 °C within 2 h and then from 21.1 to 5 °C within 4 h (in total 6 h). The cooling speeds of the first and second steps are 0.30 and 0.07 °C min^{-1}, respectively. In other words, the average cooling speed from 52.2 to 5 °C is approximately 0.15 °C min^{-1}. According to The Food Standards Agency of the UK (FSA, 2016), hot food must be cooled in 2 h from 63 to 8 °C (cooling speed is nearly 0.46 °C min^{-1}). In the "Defence Catering Manual" (MoD-UK, 2014), it is indicated that cooked food must be chilled from 63 to 5 °C within 90 min with a speed of around 0.65 °C min^{-1}. In those requirements, there is no indication about the capacity of the foodstuff to be cooled. If a refrigerator manufacturer claims a compartment with a rapid cooling feature, it shall declare a maximum loading capacity to be inserted into it. For a rapid cooling, the cooling speed must certainly be above 0.07 °C min^{-1}.

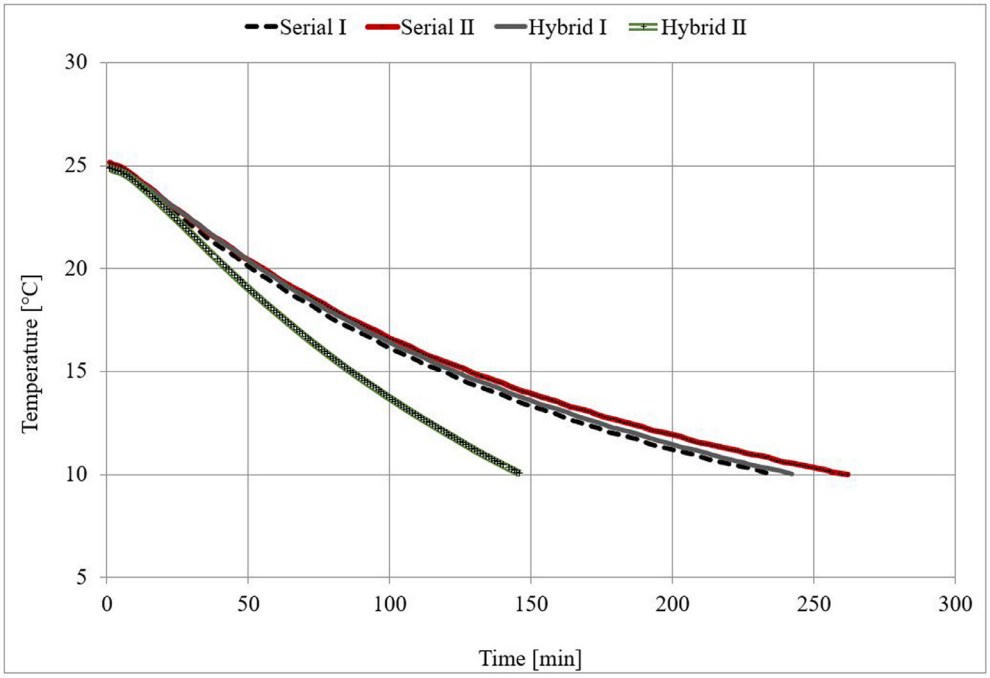

Fig. 12. Cooling down time of the refrigerators according to IEC 62552:2015.

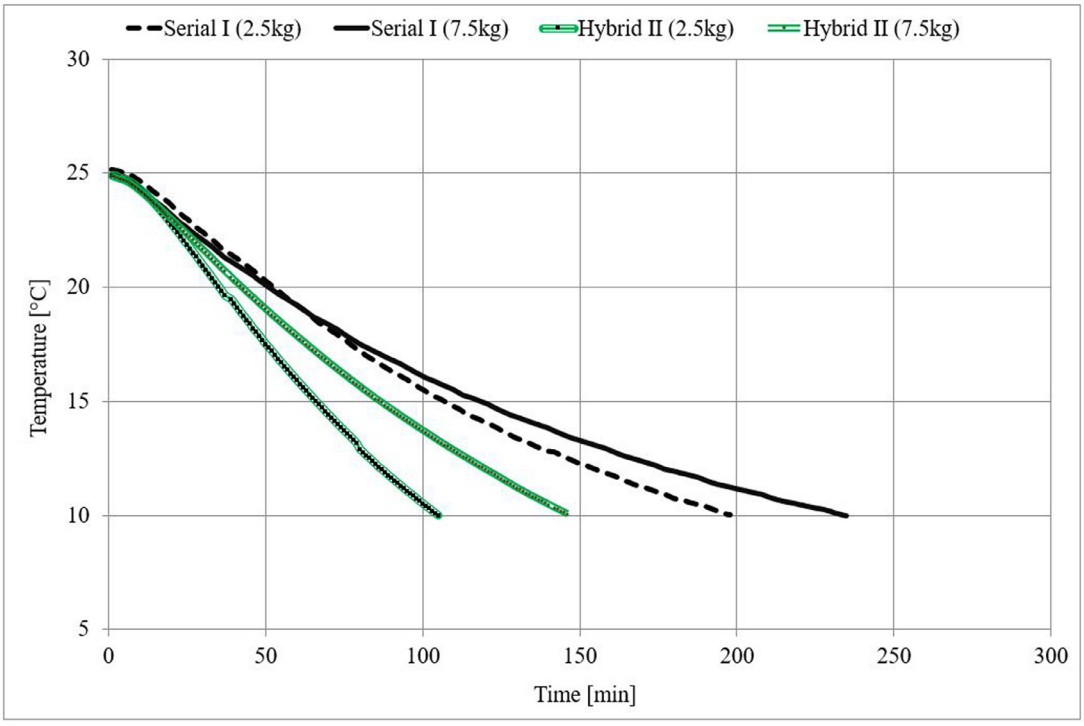

Fig. 13. Cooling down time of Hybrid II and Serial I with different amount of warm packages.

Because only the FFC is loaded, the results according to IEC 62552:2015 are to be discussed in terms of rapid cooling. This enables us to figure out the effect of TEC on the cooling performance. Fig. 12 demonstrates the temperature curves which show the temperature change of the warm packages with time for each refrigerator. The loaded amount is 7.5 kg. Hybrid II has a cooling speed of 0.10 °C min^{-1} while the others have speeds of 0.06 °C min^{-1}. With respect to Dixon & Hall-Campell (2016) Hybrid II's FFC can be considered as having rapid cooling feature.

Fig. 13 presents the results of the tests conducted with Hybrid II and Serial I with different amount of warm packages (Because Serial I had better results than Serial II, it is compared with Hybrid II). If the amount is decreased to 2.5 kg, the Hybrid II's cooling time drops significantly to 104 min with a speed of 0.14 °C min^{-1}. Its reaction to a smaller number of packages was more positive than the Serial I's.

The results are very promising. If a special design is made for this feature inside the FFC (or in any unfrozen compartment) it is possible to cool a significant amount of foodstuff in minutes.

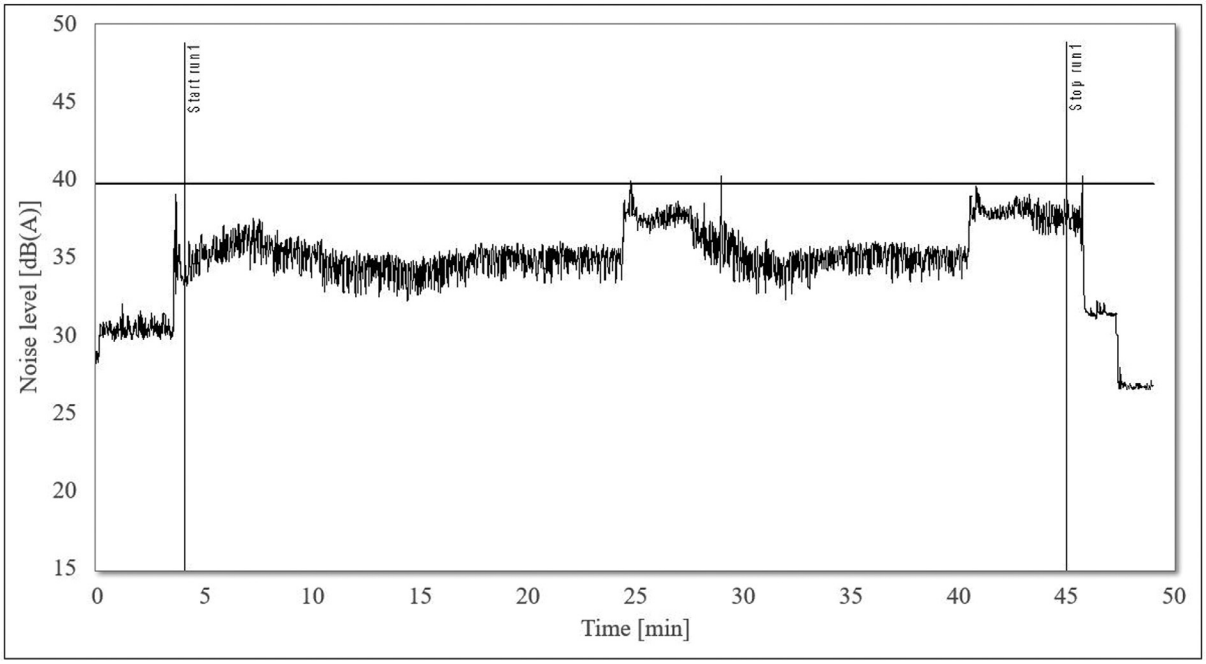

Fig. 14. Noise level of Serial I.

Table 8
Compartment target temperatures and loading conditions for freezing capacity tests.

Standard	Ambient	FFC		CC		FC	
	(°C)	Target temp.(°C)	Measured by	Target temp.(°C)	Measured by	Target temp.°C)	Measured by
EN 62552:2013	25.0 ± 0.5	≤ +5.0	Packages	−2.0 ≤ Tcc ≤ +3.0	Packages	≤−18.0	Packages
IEC 62552:2015	25.0 ± 0.5	≤ +4.0	Packages	Not measured	Packages	≤−18.0	Packages
IC 15068	25.0 ± 0.5	≤ +4.0	Packages	≤ +4.0	Packages	≤−18.0	Packages

5.4. Freezing capacity

The objective of the test is to measure the freezing capacity of the food freezers and freezer compartments (EN-62552:2013, 2013; IEC-62552:2015, 2015).

In terms of method, this test is like a cooling capacity test. The freezer compartment is first loaded with cold packages but an empty space is reserved for warm packages. The warm packages are kept at 25 °C ± 0.5 °C. Once stable conditions are met, if there is no super freezing function, the warm packages are inserted into the freezer. Afterwards, the warm packages are frozen, with their temperature dropping from 25 to −18 °C and the time is recorded. If there is a super freezing function, after stable conditions are met, this function is activated for a given time (super freezing time) indicated in the user manual of the refrigerator. As soon as this time is completed, the warm packages are introduced into the freezer compartment.

The target compartment temperatures and the loading conditions are presented in the Table 8.

The freezing capacity test results are given in Table 9. It is clearly seen that there are no significant differences in the freezing time of reference and hybrid refrigerators.

One could expect a decrease in the freezing time of the hybrid refrigerators since one of their compartments has its own separate cooling system. Namely, compressor-based system is supposed to spend more time to freeze the warm packages throughout the freezing process. To figure out this, we should refer to the compressor run time of the refrigerators. Table 10 presents the ratio of the compressor run time for each compartment during the freezing capacity tests of serial and hybrid refrigerators. The FC has already had the highest share in the run time of serial ones over the other compartments with an average value of 85.6%; consequently, there is less room for improvement. Even though run time for Hybrid II's FC increased to 95.1%, this had almost no effect on the freezing performance.

There are other key factors that affect the freezing time such as the instant temperatures of the warm and cold packages in the moment of loading, loading duration and deviations in temperature measurements. In each test, the temperature variations be-

Table 9
Overview of freezing capacity test results.

Standards	EN 62552:2013	IEC 62552:2015	IC 15068	
FC super activation	*Yes*	*yes*	*no*	*yes*
Freezing time	[h]	[h]	[h]	[h]
Serial I	19.7	–	24.4	12.8
Serial II	19.2	11.3	27.8	14.2
Hybrid I	20.4	10.7	28.2	13.4
Hybrid II	17.6	11.3	26.6	13.8

Table 10
Compressor run time ratio (CRTR) for each compartment during freezing time.

Standard	EN 62552:2013			
	Serial I	Serial II	Hybrid I	Hybrid II
FFC, CRTR [%]	7.9	9.5	11.0	0.0
CC, CRTR [%]	5.4	6.0	0.0	4.9
FC, CRTR [%]	86.7	84.5	89.0	95.1

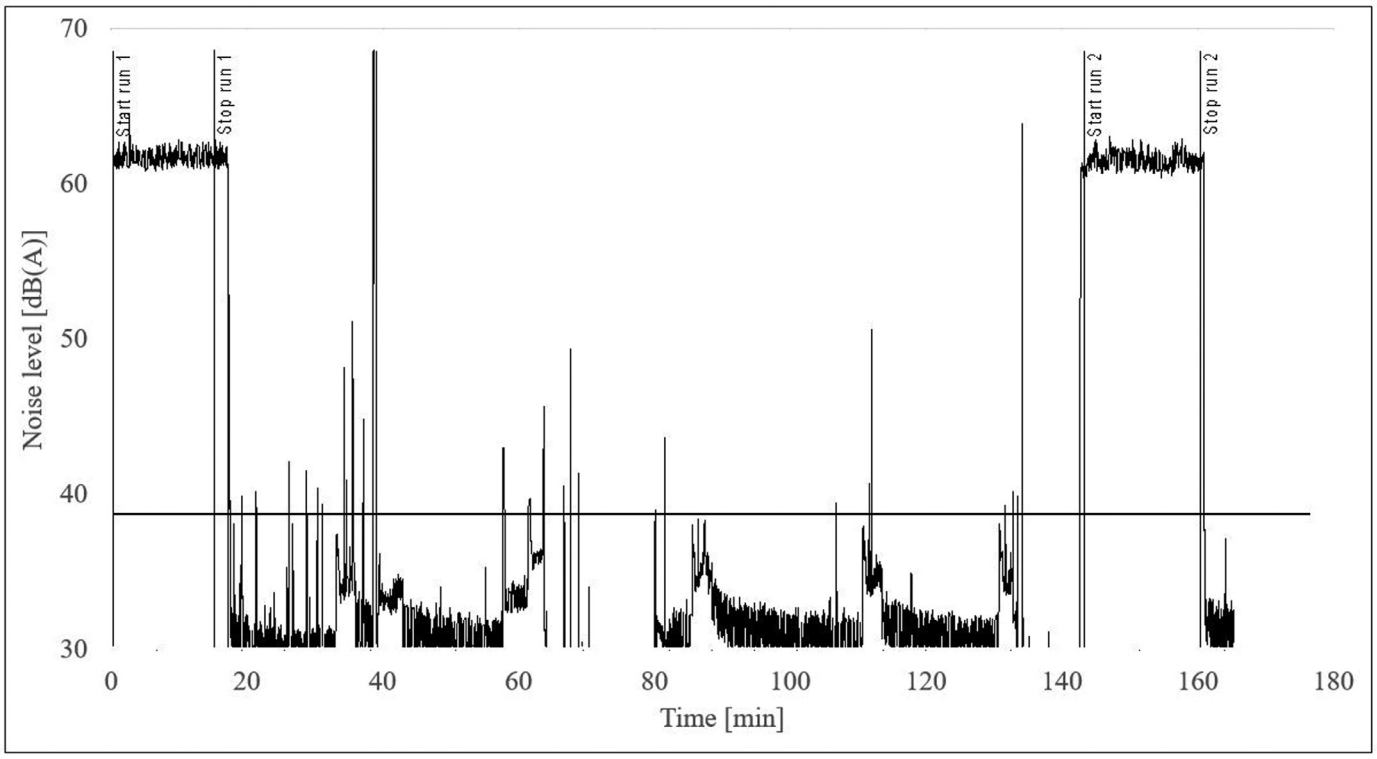

Fig. 15. Noise level of Hybrid I.

Table 11
Average noise test results.

Noise level dB(A)	Models
35.6	Serial I
35.6	Serial II
62.2	Hybrid I
65.1	Hybrid II

tween the warm packages were kept at ± 0.1 °C. The differences in average temperature of warm packages in the tests are maintained at ± 0.3 °C. Additionally, it was made sure that the allocated time for the loading was less than 1 min. Accordingly, even though there is a probable enhancement due to increase in the FC compressor run time, this may be eliminated by these factors.

5.5. Noise test

The fans are located on the finned heat sinks of the TEC in order to increase heat transfer. The fans significantly improve heat removal through the heat sinks and therefore enhance the overall performance and COP of the TEC (Astrain et al., 2016). Although in the TEC core system there are no moving components, using fan could lead to high noise level, thus eliminating one of its key advantages.

In the datasheet of the TEC, the external fan rate is given as 51 dB(A). It was therefore assumed that hybrid refrigerators could have higher noise levels compared to the serial ones which have a noise declaration of 38 dB(A).

In Table 11, the average noise results are given. Hybrid refrigerators' noise levels are almost twice those of serial ones. In Figs. 14 and 15, the noise test diagram of Serial I and Hybrid I are shown, respectively to further demonstrate the effect of the TEC fan on the noise level. In Serial I, the noisiest component is the compressor and it is followed by the evaporator fan. As presented in Fig. 14, even the maximum noise level of Serial I did not exceed 40 dB(A). However, Hybrid I's maximum noise level is up to 65 dB(A) which is triggered by the external TEC fan, see Fig. 15.

6. Conclusions and further work

Effects of current commercial TECs on the performance of household refrigerators were investigated. Analysis focused on the benefits of TECs so as to provide opportunities for the application of the thermoelectric cooling technologies. To do this, two serial refrigerators were tested to collect reference data. Afterwards, hybrid refrigerators were built by attaching TECs to the walls of the serial refrigerators' body. The same test procedures were followed and then the hybrid refrigerators' test results were compared to the results of the serial ones.

Hybrid I and Hybrid II operated under different conditions at ambient temperatures of 16, 25 and 32 °C successfully. They achieved their target compartment temperatures.

Energy consumption of the hybrid refrigerators is higher than those of serial ones. The fundamental reason for this is the low COP of TECs. Lower COP levels lead to higher power consumption. Another key reason is higher heat transmission losses through the TECs. In this experimental study, the applied TECs have an on-off cycle. Rather than using on/off operation, continuous running of TECs could be more effective and would eliminate heat flow into the cabinets. The other solution is to change the location of the TECs and make a new design in order to decrease the run time of the TEC and reduce transmission losses when the TEC is off.

In terms of the cooling capacity test, it was proved in this study that the TECs are able to cool 17.5 kg of loads from an ambient temperature of 25 °C to the desired temperature as mentioned in Part 5.3.2. A special interest is given to Hybrid II because it has the best performance; its cooling time is 30–40% less than those of the others.

A freezing capacity test does not directly measure the influence of the TEC on the refrigerator performance. It is clearly seen that there are no significant differences in the freezing time of reference and hybrid refrigerators. Although one could expect a decrease in the freezing time of the hybrid refrigerators since one of their compartments has its own separate cooling system, such a situation did not come up in our tests.

Hybrid refrigerators' noise levels are much higher than those of serial ones. Higher noise levels of hybrids are triggered by the external TEC fan. The solutions can be: (1) mounting a fan on the hot side of TEC with less noise rate, (2) increasing heat sink surface area of TEC hot side and removing fan and (3) implementing a different heat sink to the hot side of TEC without using a fan (for example, heat pipes). Yet, the proposed last two solutions will not be as efficient as the one with fan. In the next phase of this study, the improvement of noise levels of hybrid refrigerators will not be targetted. In this work, it is simply aimed to present effect of TEC's fan on the noise level of refrigerators.

It is certain that although thermoelectric cooling technology is less efficient compared to the compressor-based system, it brings significant benefits in terms of lower cooling times and better temperature stability as shown. Therefore, this technology can be applied to household refrigerators to meet the particular needs of the end users in the short term.

The outputs of this study will be the basis for further works in which Hybrid II is going to be the main focus due to the promising energy consumption and cooling capacity test results compared with Hybrid I. The test data of this initial investigation will be used in numerical simulations to find out the most suitable location of TEC. In addition to this, improvement steps will be applied to enhance the overall performance of Hybrid II.

Acknowledgments

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