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Full Length Article

Energy efficiency and transient-steady state performance comparison of a resistance infant incubator and an improved thermoelectric infant incubator

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ABSTRACT

The present study aims to contribute energy related research by comparing thermal hydraulic performance parameters including energy consumptions, set temperature precisions and noise levels of newly improved thermoelectric infant incubator having thermoelectric heat pump and existing resistance infant incubator. For that purpose, an experimental set-up has been established and equipped with necessary measuring instruments and control units which allow determination of the above-mentioned performance parameters in transient and steady state operation mode of both infant incubators. According to the experimental results, the thermoelectric system was able to control the mean temperature of the hood with a precision of 0.05 °C while precision of the resistance system was 0.1 °C. Since incubators are generally used in heating operation mode, the coefficient of performance ($COP_{heating}$) value of the thermoelectric system in the steady state condition where the mean hood air temperature is 36 °C and the ambient temperature is 25 °C, which is around 1.4, was higher than the resistance system. Thanks to the cooling mode of the improved thermoelectric system, it was shown that transient period can be shortened for lower set temperatures without opening the hood and operate in high ambient temperature (30 °C and above) environments and in transport incubators.

1. Introduction

Thousands of babies are born every day in the world, and the gestation period of the babies born normally lasts between 38 and 42 weeks. If, for any reason, the birth takes place before 37 weeks, it is called “preterm delivery”, and a baby born before their normal period is called “premature baby” [1–3]. Premature babies can be classified according to the number of gestational weeks at which birth takes place and birth weight of the newborn baby. They are classified depending on the number of gestational weeks such as extremely preterm (less than 28 weeks), very preterm (28 to 32 weeks) and moderate to late preterm (32 to 37 weeks) while they are defined according to the birth weight as low birth weight (LBW) which is 2500 g or less, very low birth weight (VLBW) that is less than 1500 g and extremely low birth weight (ELBW) which is less than 1000 g [2–5]. One of the biggest problems with newborn premature infants is that babies cannot regulate their own body temperature. When not intervened, this situation poses serious problems that may cause from permanently damage to death in infants. Depending on the gestational age and birth weight of the premature infants, the neutral thermal environment, which is the oxygen concentration consumed by the baby is minimum, are changing sensitively [6]. Since this ambiance cannot be provided to babies, thousands of babies have serious permanent health problems every year. Therefore, infant incubators are widely used to prevent these health problems [7–9]. Premature infant incubators are medical devices that regulate proper temperature, relative humidity and oxygen levels needed by newborns in a controlled manner. After the invention of the first modern incubator in 1891, many incubator designs with different models and working principles were developed [10]. The infant incubators currently used provide the neutral thermal environment temperature for the premature baby using an electrical resistance as the heating element. However, it has been determined that these systems have some problems in creating the neutral thermal environment in the hood, especially in cases of hyperthermia which is an uncontrolled increase in body temperature and ambient temperature changes. An infant incubator operating with a thermoelectric heat pump has been improved to eliminate all the problems experienced in

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Nomenclature

A	Cross-sectional area of p&n type thermoelement material (m^2)
COP	Coefficient of performance
$COP_{heating}$	Coefficient of performance for heating
$COP_{cooling}$	Coefficient of performance for cooling
I	Current (A)
I_{max}	Maximum current (A)
k	Thermal conductivity of p&n type material (W/m.K)
k^*	Effective thermal conductivity (W/m.K)
K	Thermal conductance of TEC module (W/K)
l	Leg length of p&n type material (m)
n	Number of thermocouple (p&n number)
$\dot{Q}_c$	Cooling power of TEC module (W)
$\dot{Q}_{c\ max}$	Maximum cooling power of TEC module (W)
$\dot{Q}_h$	Heating power rate (W)
R	Internal resistance of TEC module (Ω)
T_c	Cold surface temperature of TEC module (K)
T_h	Hot surface temperature of TEC module (K)
ΔT_{max}	Maximum temperature difference (°C)
V	Voltage (V)
V_{max}	Maximum voltage (V)
$\dot{W}$	Electrical power consumption (W)
Z	Figure of merit (1/K)
Z^*	Effective figure of merit (1/K)

Greek symbols

α	Seebeck coefficient (V/K)
α^*	Effective Seebeck coefficient (V/K)
ρ	Electrical resistivity (Ω.m)
ρ^*	Effective electrical resistivity (Ω.m)

Subscripts

n	n type material properties
p	p type material properties

these cases and to achieve a more precise and homogeneous temperature distribution inside the hood [11,12].

Thermoelectric is related to heat and electricity, and thermoelectric effect is called the direct conversion of temperature differences to electric voltage or vice versa via a thermocouple which is formed by connecting p- and n- type semiconductor materials together with conductors in series. When a temperature difference is applied to both ends of the thermocouple, it creates a direct current (DC) voltage (Seebeck effect) [13]. On the contrary, when a DC voltage is applied to it, heat is transferred from one side to another depending on the current direction applied, and the temperature difference between two ends is obtained (Peltier effect). In most applications, since one thermocouple is not sufficient to provide the desired performance, thermoelectric module is created by connecting to the semiconductor materials each other electrically in series and thermally in parallel. When the thermoelectric module is used for power generation, it is called a thermoelectric generator (TEG), while the module is called a thermoelectric cooler (TEC) when it is used for heating and cooling purpose [13–15]. Today, many studies and applications involving TEG or TEC modules and systems are carried out. These studies and applications for TEG can be categorized under 6 broad categories: space research and applications, waste heat recovery studies and applications, TEG research and applications combined with renewable energy systems, TEG studies and applications used in microelectronics and sensors, solar TEG studies and applications and finally organic TEG research and applications [16]. On the other hand, TEC can be categorized under 4 categories as civil market studies and applications, cooling/heating researches and applications in automobile industry, cooling studies and applications in electronic devices, and thermoelectric conditioning studies and applications [17]. At the same time, TEG and TEC systems have been widely used in medical applications recently. Thermoelectric systems in medical applications are divided into two main categories: solid state cooling-heating in medical applications and thermoelectric energy harvesting for self-powered biomedical devices which are divided into two in itself as implantable medical devices and wearable applications [18]. In this study, a research related to solid state cooling-heating in medical applications part of TEC systems was conducted.

Cooling-heating in the medical applications takes place with the Peltier effect, which acts as a solid-state heat pump. These devices transfer heat from one surface to the other depending on the direction of the applied current. Although TEC systems have high costs and low efficiency, they are widely used in special medical applications thanks to their ability to quickly cool/heat and easily reverse without a moving part. Today, one of the most common biomedical applications of the TEC modules is the thermal cycles of polymerase chain reaction (PCR) that is a method used in the process of replicating DNA molecules. The replication process takes place in three steps: denaturation at 94 °C, annealing at 54 °C and extension at 72 °C. In these steps, the reversibility, fast response and ease of application of the TEC modules make them ideal for PCR devices [18]. Besides, high heat flux is applied cyclically to the thermoelectric modules during the PCR process and as a result, mechanical stresses occur within the modules. Therefore, the thermoelectric modules used in cycling applications are expected to be resistant to the process. Volkov et al. [19] developed a highly reliable miniature thermoelectric module under RMT Ltd. company using a new technology that eliminates this problem. The module resists more than 500.000 heating–cooling cycles at temperatures ranging from 20 to 100 °C with a rate of 20 °C/s. It is known in medical science that moderate temperature effects are an important factor in the treatment of many diseases of humans and living things. Accordingly, Yavuz et al. [20] have designed a computer controlled cold-hot therapy device operating with TEC modules. That device could balance the body temperature by applying cold and hot treatment to the desired region of the body in cases such as injuries, fever, traumas, etc. Whether the designed device reaches the desired temperatures (0–15 °C for cooling and 40–45 °C for heating) quickly was tested with different powers supplied to the TEC module, and it was shown with the test results obtained that the developed device could provide the desired temperature range. Similarly, it is stated that approximately half of the spinal diseases are nervous system diseases, and 80% of them occur as lumbar centered spinal cord injury. For that, Anatychuk and Kobylyansky [21] used TEC systems in the treatment of radiculitis and spinal massage and developed a device that could control the temperature change determined by the doctor depending on the time. It could operate in the temperature range of −20 to 50 °C, and the temperature change rate could reach 5–10 K/s. Then, Anatychuk et al. [22] developed a computer method and algorithm that calculates the optimum time dependency of the thermoelectric converter supply current, which enables precise control of the desired temperature in thermoelectric devices used in the medical applications. Since TEC is simple, compact, noiseless and portable, it is convenient to be used in the transportation of biomedical products (vaccine, blood, organ, etc.) where the temperature must be kept at certain value in order to be carried safely. For these products, Güler and Ahiska [23] have designed and developed a microprocessor controlled portable thermoelectric medical cooling kit. With a single TEC, this device can keep the products in it the between 0 and 8 °C according to the user's preference, and it is able to heat up to 37 °C which is the human body temperature, especially before using the product. In addition, Güler and Ahiska considered the effect of the ambient temperature parameter and tested the medical kit depending on the ambient temperature varied between 25 and 50 °C. They determined that the temperature in the kit could remain between 6 and 10 °C in all tests. In another medical kit design, Wang et al. [24] found the optimum wing length 0.598 m and optimum fin thickness 0.0025 m for a blood cooler medical kit operating with TEC by heat transfer analysis, and experimentally tested the change in temperature inside the kit according to the loading and without loading condition in the medical kit. According to the results, they determined in the without loading condition that the cabinet temperature drops to 2 °C within 40 min, and the optimum fin thickness provides the desired cooling performance, provided that the ambient temperature remains constant at 25 °C. In the loading condition, they placed 10 test tubes in the cabinet, and stated that the system was be able to provide safely the cabinet temperature between 2 and 10 °C. Similarly, He et al. [25] conducted the theoretical and experimental research of the thermoelectric refrigerator box used for medical services and Nohay et al. [26] designed and manufactured a portable thermoelectric refrigerator powered by solar energy for insulin storage. Another potential medical application area using thermoelectric technology is therapeutic hypothermia. Body temperature control of an injured human being is very important in brain traumas, cardiac arrests, asphyxia and excessive blood loss. Because when the center of the human brain is cooled to 30–32 °C, human is able to live without blood, oxygen and glucose for 45–60 min even when the heart stops [27,28]. Kapidere [27] designed a thermo-hypothermia medical device with a microcontroller control by creating a thermoelectric helmet which has 8 temperature sensors and 120 flexible TEC modules to quickly cool the brain. The test results of the designed device have shown that the device operating with the TEC modules could be used to protect the brain and kept constant at the desired temperatures. After in just a few years, Yavuz [28] developed this system further by controlling it with 70 flexible TEC modules, 140 W cooling capacity and a fuzzy logic with heating rate control not exceeding 0.5 °C/min. In another study, Tauchi et al. [29] improved the focal brain cooling device that operates with a thermoelectric heat pump and validated the neuroprotective effect of the device by testing it in rats. The results obtained showed that it is protective against some injuries (acute ischemic injury, progressive damage of the penumbra, and reperfusion injury), especially targeted temperature management at 33 °C. Due to the limited energy resources in the world and also the increasing need for energy day by day depending on the increasing population number, it is very important to use energy resources efficiently. Patel et al. [30] determined that 4% of the electrical energy used in residences in USA is consumed by clothes drying machines, and they designed a new clothes dryer that operates with a thermoelectric system to saving energy. In the study, the mathematical modeling of the thermoelectric dryer was created, and the accuracy of the model was proved by experimental studies. In addition, it has been shown that the improved system with the experimental results is 85% more efficient than the electric resistance clothes dryers.

Although there have been many studies on the use of TEC modules for heating and cooling in medical applications, a research aiming the experimental investigation and comparison of dynamic behaviors and thermal–hydraulic performance parameters of a resistance infant incubator and an improved thermoelectric infant incubator has, to the best of our knowledge, not been reported. The main objective of this paper is to compare head-to-head of the resistance (existing) infant incubator and the thermoelectric infant incubator operating with a thermoelectric heat pump which performs both heating and cooling requirements for premature babies on the same device and provides more precise temperature control than the resistance incubator systems. For that, the advantages and disadvantages of both systems are experimentally investigated. In addition, it is analyzed whether the improved thermoelectric incubator overcomes the above-mentioned problems in the resistance incubator.

2. Experimental method

A commercial infant incubator is needed for the experimental comparison of two systems (resistance and thermoelectric incubator) each other, and thus AMS Amenity XP premature infant incubator manufactured in 2006 was purchased. In order to develop the thermoelectric incubator system, firstly, the current design parameters of the AMS Amenity XP incubator which are heating powers, heating and cooling rate times, mass air flow rates, fresh air quantity and so on must be accurately identified (Fig. 1a). Using the design parameters determined in the conservation equations of the thermoelectric heating–cooling system, the thermoelectric heat pump system was optimized. Depending on these parameters, the optimum heating–cooling powers, maximum COP value, optimum number of thermocouples, number of TEC modules, fin geometries, fan flow rates of the system was determined [11,12] (Fig. 1b). In order to compare the dynamic behavior and thermal–hydraulic performance parameters of the resistance incubator and the improved thermoelectric incubator, it has to be established the appropriate experimental setup of both systems.

2.1. Design parameters and experimental setup of the resistance incubator system

The amount of fresh air taken from the surrounding environment into the incubator, the amount of air taken from the hood environment, the speed distribution within the hood, the temperatures of the critical points of the incubator system, the noise level in the hood with and without alarm, current, voltage and power consumption were determined as the design parameters of the resistance incubator system. In order to determine the above-mentioned design parameters correctly, the experimental set-up in shown Fig. 2 has been established. Thermocouples were placed at 5 different points specified in the EN 60601-2-19 standard [31] for temperature distribution in the hood environment. In addition, 12 thermocouples were located in the existing system in order to use in mathematical calculations and to compare the resistance system with the thermoelectric heat pump system. In this way, the temperatures at each critical point of the incubator were measured and recorded instantly via the data logger. A reference thermometer was inserted at the center of the hood for both setting of thermocouples and accurate comparison of two systems. Since the noise level in the premature baby is very important, the noise level of the existing system was measured and recorded instantly. In order to determine the total power consumed by test apparatus and the resistance incubator system, all instruments were connected to the energy analyzer by means of a multi socket. Thus, the amount of current, voltage and total power consumed by the resistance incubator system was determined for each experiment performed (Fig. 2).

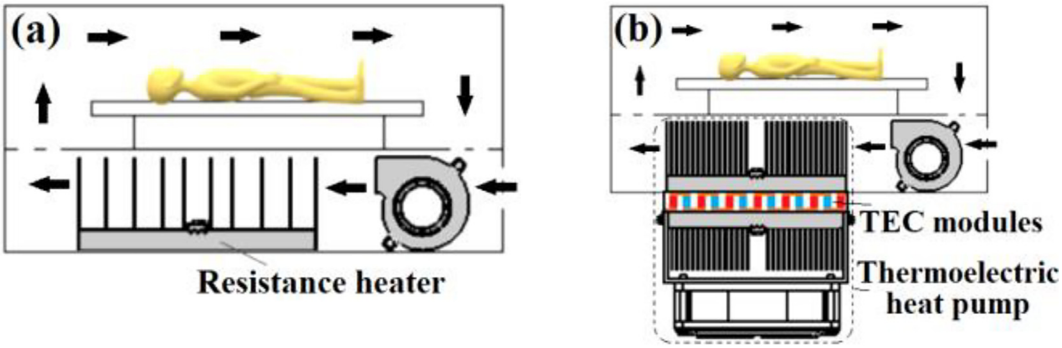

Fig. 1. Schematic diagram (a) resistance heater (b) thermoelectric heat pump.

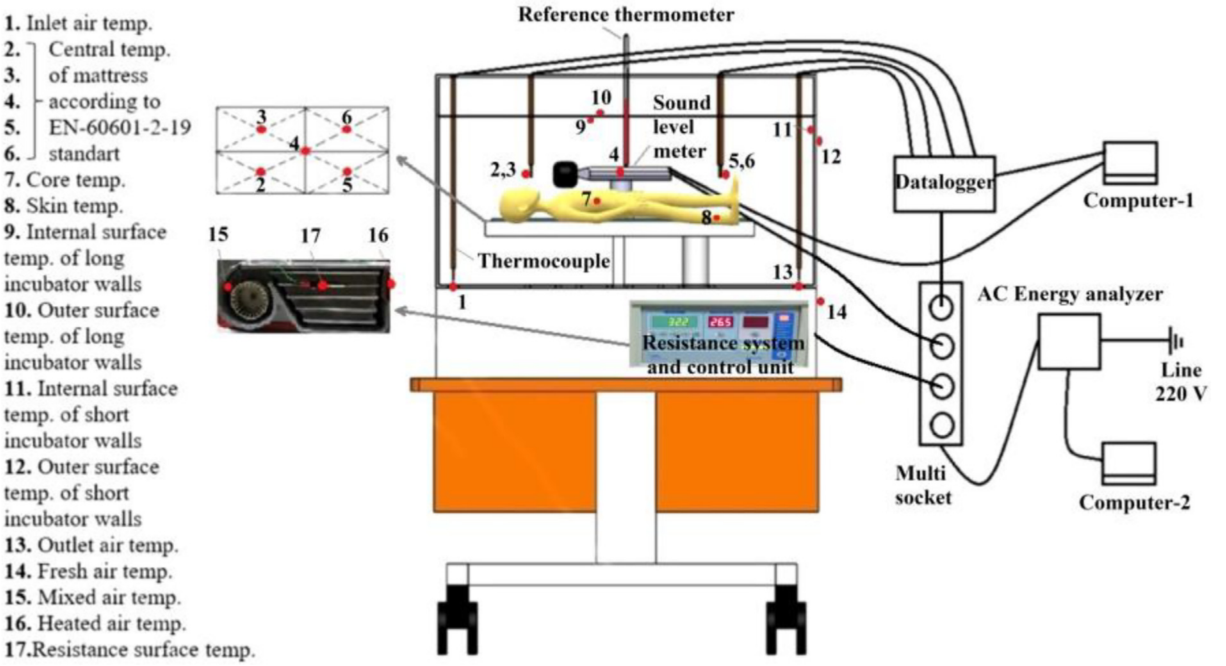

Fig. 2. Schematic experimental setup of the resistance infant incubator with manikin.

2.1.1. Determination of air flow velocities and rates

In the AMS Amenity XP incubator, 3 air velocities which are the fresh air velocity, the air velocity taken from the hood environment and the average velocity of the air in the hood should be determined (Fig. 1). The AMS Amenity XP incubator draws some fresh air from the ambient environment through an annular duct opening to the outer environment. Since the velocity values vary at each point in the circular channel, it is very important to accurately determine the average velocity within this channel. That is why the average velocity measurement method used by Bureau of Energy Efficiency [32] to determine the volumetric flow rate of the fans was used.

While some fresh air is drawn from the ambient environment by the radial fan through a circular duct opening out, some air is sucked from the hood environment simultaneously thanks to a gap opening to the hood environment. Then, by mixing the air taken from these two environments, the mixed air is passed over the heating element and sent to the hood. In the AMS Amenity incubator, it is easier to measure the flow rates and average velocity of the mixed air than to measure the average velocity and flow rate of the air sucked from the hood environment. Then, the amount of air sucked from the hood can be calculated by subtracting the amount of fresh air from the amount of mixed air. The mixed air passes through a rectangular duct, and the air velocity at each point in the rectangular duct is different, as in the determination of the amount of fresh air. For that, the measuring region is divided into equal rectangular areas. For the rectangular ducts, the Bureau of Energy Efficiency [32] recommends dividing the measuring region into equal areas ranging from 16 to 64. In this study, the measuring region is divided into 16 equal rectangular areas.

The average air velocity in the hood should be at a low speed so as not to disturb the baby. As clearly stated in the incubator standard [31], the air flow rate on the mattress must be less than 0.35 m/s. It is very difficult to accurately determine the average velocity in the hood. Because the cross-sectional area of the hood in contact with the low air flow rate is very large. Furthermore, in the AMS Amenity XP incubator, it makes it even more difficult to determine the average velocity of the hood air as the air enters to the hood through openings on both short edge and long edge (Fig. 3). No method has been found in the literature to determine the average velocity of the airflow having such a complex geometry and a very large cross-sectional area according to the low flow rate. In this study, the cross-sectional area of the hood was divided into 85 small squares with a cross-sectional area of 3x3 cm^2 for the

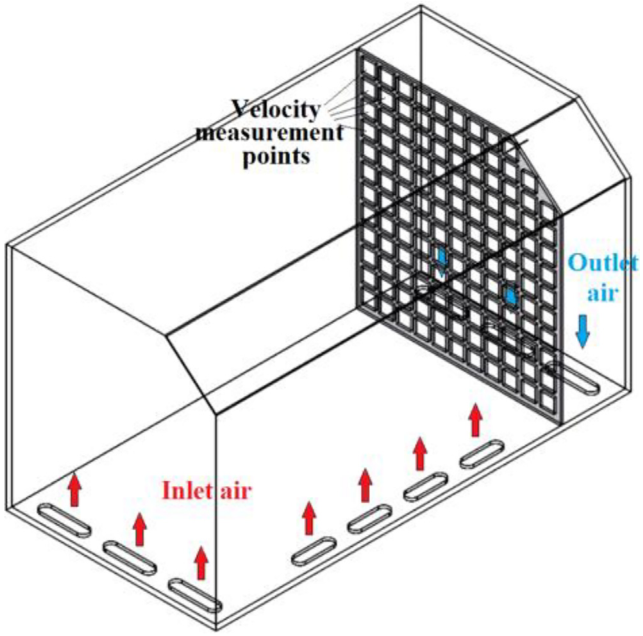

Fig. 3. Determination of the average velocity of air in the hood.

determination of average velocity of the air in the hood. The centers of these small squares were located, and fixed measuring points were determined. The velocities measured at the fixed measuring points were summed and divided by the number of measuring points. In this way, the average air velocity in the hood is tried to be determined accurately with the velocities measured at many points (Fig. 3).

In order to determine the magnitude of the average velocities of fresh, mixed and hood air, Testo 435–3 anemometer operating according to the hot wire measurement method was used. Since the velocity values in the infant incubator are very small, a high-precision Testo 0635–1025 probe was selected. In order to accurately determine the average velocities of fresh, mixed and hood air in the resistance infant incubator, velocities were measured for 1 min with the hot wire measuring probe at the fixed points determined according to Bureau of Energy Efficiency [32]. Velocities at each point were determined using the averaging of the velocities measured by the instrument over the specified measurement time. In order to minimize the error in the measurements, the velocity measurements at these points were repeated 3 sets. The average velocities obtained at the end of 3 sets were also averaged, and the average velocities representing the flow rate distribution of fresh, mixture and hood air were determined. After the average velocity is obtained, the volumetric and mass flow rates of fresh, mixed and hood air were obtained by using the cross-sectional areas through the flow and the density of the air at 25 °C which is 1.184 kg/m^3. Since the speed distribution, volumetric and mass flow rates of the resistance system are always constant, these values were determined only once and used in all experiments.

2.1.2. Determination of temperatures

In order to function properly an infant incubator, it must first meet the temperature criteria specified in the incubator standard [31]. In addition, in order to compare the resistance incubator system with the improved thermoelectric incubator system, it is necessary to record the changes of the temperatures at critical points over time. The average hood temperature was determined by measuring the temperature of 5 different points which are 10 cm above the mattress, as specified in the incubator standard [31]. The locations of the other critical points recorded the temperature measurement are given in detail in Fig. 2. In this way, a total of 17 thermocouples were placed at critical points of the resistance incubator system, and the temperature changes taking place in each experiment were recorded instantly via the data logger.

In the infant incubator systems, T and K type thermocouples are widely used since the temperatures generally vary within the narrow temperature range (10–150 °C). In this study, the thermocouples, data logger and data logger software were obtained from Elimko Co. Ltd.. In order to measure the temperatures, T types of E-TC15-K-T-K20-TT portable thermocouple used in surface measurements and calibration processes, and E-680-32-2-0-00-1-0 data logger that has 32 independent channels and can send data via the E-IB-11 USB converter were preferred. At the same time, a package software used by the data logger can be set the thermocouple type, junction point type, sensitivity, etc. of each channel, and temperature data measured in each channel, depending on the date and time, can be saved as an excel file. Although the selected E-TC15-K-T-K20-TT portable thermocouple is a sensitive thermocouple, thermocouple is ultimately formed by welding two different materials. Due to some uncertainties at this welding point, each thermocouple produced under the same conditions may show any temperature value differently with small deviations. Therefore, each thermocouple was calibrated in a water bath according to the reference thermometer, and the correction equations generated for each thermocouple were programmed into the data logger.

2.1.3. Determination of noise level values

Premature babies are very sensitive to all the factors around them because they open their eyes to the world before some organs develop sufficiently depending on the degree of premature. Therefore, premature infants can mostly live in neonatal intensive care units (NICU) at the beginning of their lives. These delicate babies can be exposed to high levels of noise, especially in these NICU due to the operation of different devices and the alarm sounds in the hospital. In newborns, high noise can cause hearing and sleep disorders and somatic effects. Moreover, it is clearly stated in EN 60601-2-19 [31] that the noise should not exceed 60 dB in normal operation of the incubator and 80 dB when the audible alarm in the incubator is activated. Therefore, in this study, both the noise levels of the resistance incubator system (with and without alarm) and the improved thermoelectric incubator system were measured with CEM DT-8852 which is sound level meter and can be instantly saved the measured data to the computer environment as an excel file via USB connection. The sound level meter was located 10 cm above the center of the mattress where the baby lies down [31].

2.1.4. Determination of electrical powers consumed by the resistance incubator system

Since this study is a scientific study, it is important to determine the current, voltage and power values of the incubator in each experiment. Therefore, Entes MPR 45S energy analyzer was used to measure the electrical quantities of the systems. As clearly shown in Fig. 2, the resistance incubator system and measuring devices were connected to a multi socket, and so the entire electric consumption of the experimental system was collected in a single line. This line passed over the energy analyzer and was connected to the mains voltage line. In this way, the current, voltage and power values consumed by the resistance incubator system were measured with Entes MPR 45S energy analyzer. The measured values were transferred to the computer via RS485 usb converter as an excel file depending on the date and time.

2.1.5. Determination of dynamic behaviors

In order to investigate the dynamic behavior of the incubator systems, a manikin that simulates the real baby was placed on the incubator in the steady state conditions, and an actual situation was tried to be simulated. For that, warm water of 36.7 °C representing the core temperature of the baby was added into the manikin. Then, the hood of the resistance and thermoelectric incubator systems which were previously steady state conditions was opened, the manikin was placed, and the change in the manikin's core and skin temperatures were monitored by 2 thermocouples. To ensure standardization in both systems, the hood was closed after keeping it open for 1 min. With these experiments, both the core and skin temperature changes of the baby in both systems and the responses of the systems (dynamic behavior) whose stability were impaired were tried to be investigated.

2.2. Design parameters and experimental setup of the thermoelectric incubator system

The main objective of this study is to develop an infant incubator system which is more efficient and has more accurate temperature control than the resistance system under the same conditions and eliminates the above-mentioned deficiencies of the resistance system by removing only the resistance control unit and heating element in the existing system without changing the basic design of the incubator system. Therefore, thermoelectric infant incubator system which operates with a thermoelectric heat pump has been developed [11]. In the improved system, heating and cooling processes of the infant incubator are realized with TEC modules. Since the TEC modules operate with DC current, in addition to the experimental setup of the resistance incubator system, a DC power supply and a DC power analyzer which shows the current, voltage and electrical power consumed by the TEC modules were added. Besides, as the thermoelectric incubator system is controlled by automatic control (proportional integral derivative control, PID), a microprocessor (Arduino) and a driver that can change the direction of current for the transition of TEC modules between heating and cooling modes and allows to Arduino to control high currents must be added to the experimental setup. Accordingly, in order to determine the design and performance parameters of the thermoelectric incubator system, the experimental setup in Fig. 4 was established.

In this study, since the two systems are compared with each other, the methods and measuring devices used in the resistance incubator have also been used to determine the design and performance parameters of the thermoelectric incubator. Unlike the resistance incubator system, the 17th thermocouple function has been changed, and the 18th thermocouple has been added to the developed system. When the current direction of the TEC modules is changed, the heating and cooling surfaces are replaced. Therefore, the values measured by thermocouples 17 and 18 in heating and cooling mode have different meanings (Fig. 4).

In the improved thermoelectric heat pump system, when the voltage is applied to the TEC modules, heating on one surface of the modules and cooling on the other surface take place. The heat on the heating and cooling surfaces is transmitted to the heatsink by conduction. Then, the heats created on both heatsinks is sent to the environments by the fans. In this way, one environment is heated whereas the other is cooled (Fig. 1). If it is desired to replace the heated and the cooled environments, it is enough to change the direction of the voltage. Because by changing the voltage direction, the system starts to operate in reverse with the same way. The power of fans and TEC modules of the improved thermoelectric incubator system must be controlled with automatic control in order to be able to operate at the same air flow rates in the resistance incubator system and to provide the desired temperature in the incubator. For that, Arduino Mega 2560 was used as control element (Fig. 5). Besides, the fans and TEC modules in the thermoelectric system operate with DC voltage. Thus, since the preferred fans and TEC modules operate with 24 V and 14 V, two separate DC power supplies are needed. Particularly, high efficiency Mean Well LRS-35–12 switch mode power supply (SMPS) was used as the TEC modules draw high current and voltage while the system is operating, whereas an ordinary power supply (BRM-400-24) was used for the fans (Fig. 5). Note that the operating voltage of the power supply of TEC modules is set to 14 V with the adjustment screw. Moreover, both the fans and the TEC modules operate at a much higher voltage than the voltages from which the controller (Arduino) can control. In order for the Arduino to control these high values, drivers must be added to the system. In addition to this, in the improved system, the voltage direction of the TEC modules must be changed in order to be able to operate the TEC modules in heating or cooling mode according to the user's preference. For that, a driver with an H-bridge that provides to be changed the voltage direction of the TEC modules must be used. Considering all these parameters, 5–35 V 15 A dual motor driver was used for the fans and 5–35 V 30 A dual motor driver was used for the TEC modules (Fig. 5).

Finally, in order for Arduino to be able to control the temperature of the thermoelectric incubator system, its temperature must be measured with a temperature sensor and communicated with the Arduino. For that, Sensirion SHT31 which are temperature and relative humidity sensor with high sensitivity (±0.3 °C and ± 1 RH) was used, and the temperature sensor was located at the center of the hood and 10 cm above the mattress. In the improved thermoelectric incubator system, the incubator must detect the set temperature and provide the desired temperature with automatic control as soon as possible. Incubator standards states that in an environment where the ambient temperature is 21–26 °C, the time required for the hood air temperature to reach 36 °C is less than 45 min [31]. Therefore, the thermoelectric system was controlled by PID control. For the PID coefficients (K_P, K_I and K_D) which enable the PID controller to precisely control the temperature of the system, firstly the transfer function of the incubator system in MATLAB®/Simulink software were obtained. Then, by taking into account criteria which enable the system to be controlled quickly, precisely and with minimum overshoot and oscillation and 45 min parameter in incubator standard, PID coefficients for unit step were determined as $K_P = 65.5192$, $K_I = 6.8289$ and $K_D = 17.816$ in MATLAB®-PID Tuning interface [12]. The automatic control software of the system was created by using the PID library in Arduino.

2.2.1. Determination of electrical powers consumed by TEC modules

The total current, voltage and power values consumed in the thermoelectric incubator are measured with the Entes MPR 45S energy analyzer, as shown clearly in the connections of the experimental setup in Fig. 4. But this energy analyzer is able to measure the energy values consumed only by systems operating with alternating current (AC). In the thermoelectric incubator, heating–cooling processes are provided by TEC modules. Since TEC modules operate with DC voltage, a DC power analyzer is needed. For that, HIOKI PW3390 power analyzer was used, and by taking Root Mean Square (RMS) values of current and voltage consumed by TEC modules in the experiments, the electrical quantities of TEC modules were measured.

2.3. Methodology and uncertainty analysis

In this paper, the values measured with the measuring devices were determined by the experimental setup established as described in detail above. Using these measured values, the heat

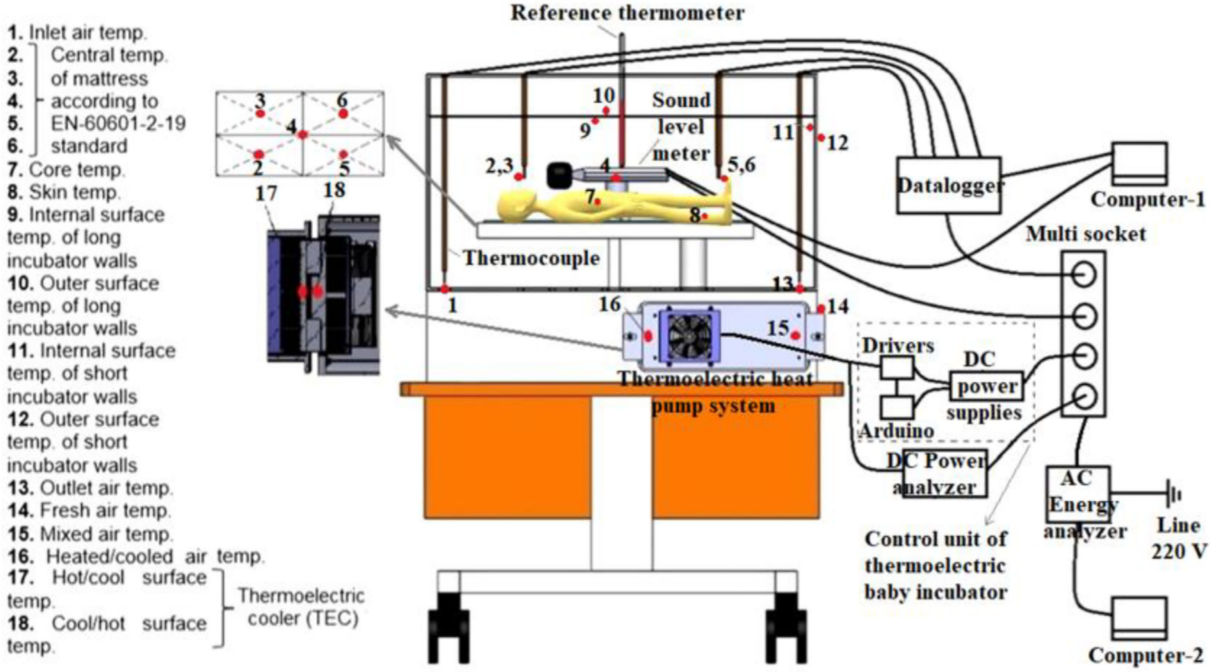

Fig. 4. Schematic experimental setup of the thermoelectric incubator with manikin.

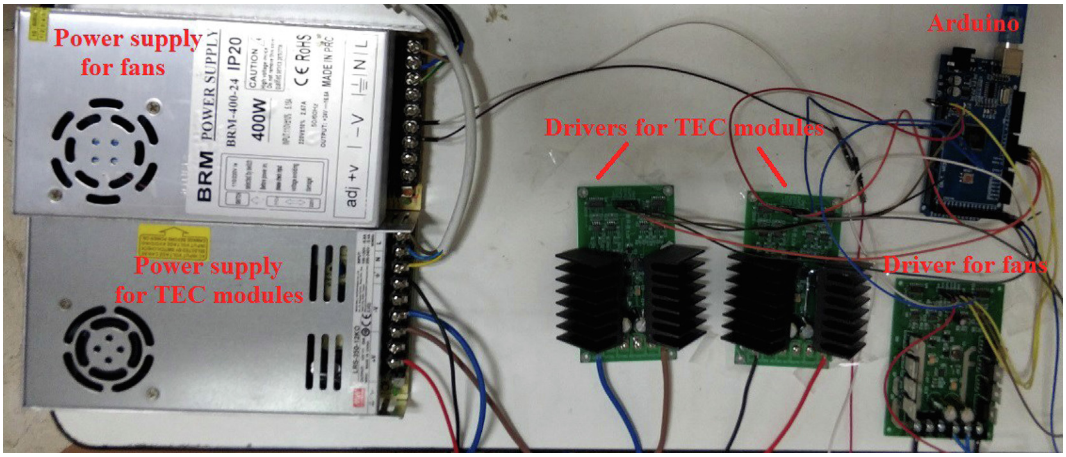

Fig. 5. Control unit of the thermoelectric incubator system.

powers absorbed/liberated from the cold and hot surfaces of the TEC modules and COP values were calculated using the ideal equations of the TEC systems subtracted by Lee [33] according to certain assumptions. Then, the heat power absorbed at the cold surface ($\dot{Q}_c$) of the TEC module consisting of n thermocouples is obtained as [33]

$$\dot{Q}_c = n \cdot \left[\alpha \cdot T_c \cdot I - \frac{1}{2} \cdot I^2 \cdot R - K \cdot (T_h - T_c)\right] \tag{1}$$

where

$$\alpha = \alpha_p - \alpha_n, \quad R = \frac{\rho_p \cdot l_p}{A_p} + \frac{\rho_n \cdot l_n}{A_n} \text{ and } K = \frac{k_p \cdot A_p}{l_p} + \frac{k_n \cdot A_n}{l_n} \tag{2}$$

Similarly, the heat power liberated at the hot surface ($\dot{Q}_h$) is expressed as [33]

$$\dot{Q}_h = n \cdot \left[\alpha \cdot T_h \cdot I + \frac{1}{2} \cdot I^2 \cdot R - K \cdot (T_h - T_c)\right] \tag{3}$$

The power consumption ($\dot{W}$) and the voltage (V) across the TEC module are determined as [33]

$$\dot{W} = n \cdot \left[\alpha \cdot I \cdot (T_h - T_c) + I^2 \cdot R\right] \tag{4}$$

$$V = n \cdot [\alpha \cdot (T_h - T_c) + I \cdot R] \tag{5}$$

$COP_{cooling}$ being coefficient of performance for cooling is written as [33]

$$COP_{cooling} = \frac{\dot{Q}_c}{\dot{W}} = \frac{n \cdot \left[\alpha \cdot T_c \cdot I - \frac{1}{2} \cdot I^2 \cdot R - K \cdot (T_h - T_c)\right]}{n \cdot \left[\alpha \cdot I \cdot (T_h - T_c) + I^2 \cdot R\right]} \tag{6}$$

Expressions obtained between Eqs. (1)–(6) are defined as ideal equations for TEC modules. If close attention is paid, it is necessary to determine the thermoelectrical material properties which are Seebeck coefficient (α), electrical resistivity (ρ) and thermal conductivity (k) in order to make a calculation using these expressions.

However, manufacturers provide the maximum performance parameters (I_{max}, V_{max}, ΔT_{max} and $\dot{Q}_{c\ max}$) in the catalog of the TEC modules whereas they do not provide the material properties. This poses a problem between TE system designer, which ask to simulate the TEC module performance using the ideal equation, and manufacturing companies. To eliminate the problem, Lee [33] developed the effective material properties concept obtained by using the maximum performance parameters given in the product catalogs. The effective figure of merit is determined as [33]

$$Z^* = \frac{2 \cdot \Delta T_{max}}{(T_h - \Delta T_{max})^2} \tag{7}$$

The effective Seebeck coefficient is given as [33]

$$\alpha^* = \frac{2 \cdot \dot{Q}_{c\ max}}{n \cdot I_{max} \cdot (T_h + \Delta T_{max})} \tag{8}$$

The effective resistivity is expressed as [33]

$$\rho^* = \frac{\alpha^* \cdot (T_h - \Delta T_{max}) \cdot \frac{A}{l}}{I_{max}} \tag{9}$$

The effective thermal conductivity is obtained as

$$k^* = \frac{(\alpha^*)^2}{\rho^* \cdot Z^*} \tag{10}$$

In this way, firstly, the effective material properties of the TEC1-127140 modules, which is n = 127, $\dot{Q}_{c,max}$=138 W, ΔT_{max} = 75 °C, I_{max} = 16.34 A, V_{max} = 16.4 V, A = 2 mm^2 and l = 1 mm, were determined [34]. Then, by substituting the effective material properties and experimentally measured terms in mathematical expressions into ideal equations, the heating–cooling powers and COP values of the TEC modules were obtained. In experimental studies, another point that is as important as the results obtained is the accuracy and reliability of the measured and calculated quantities. For that, an uncertainty analysis was performed according to the standard procedures reported by Holman [35]. It has been determined that thermoelectric manufacturers generally use precision Keithley multimeter measurement systems in determining the maximum parameters and temperatures of the TEC modules [36]. But the measurement error rates of this measurement systems cannot be found anywhere. Therefore, a reasonable assumption has been made by considering the error rates in the ordinary T-thermocouple and energy analyzer used in the experiment setup for the error rates in determining the maximum parameters and temperatures. In this context, the error rates in the maximum parameters and temperatures are determined as 0.5% in Imax and ± 0.3 °C in the temperatures, and the uncertainty analysis was conducted. In addition, the accuracy of the measurement devices used in the experimental setup is ± 0.03 m/s for velocity, 1% for dimensions, and 0.5% for current and voltage. The uncertainties in the measured and calculated quantities are given in Table 1.

3. Results and discussions

In order to compare the dynamic behavior and thermal–hydraulic performance parameters of the resistance system and the improved thermoelectric incubator system, the experimental setup of AMS Amenity XP premature baby incubator was established. The AMS incubator controlled by a PI (proportional + integral) automatic controller has two operating modes which are air and skin mode. The user selects the mode via the control panel and enters the desired temperature and relative humidity value on the control panel (Fig. 6a). This study is a preliminary investigation of the improved thermoelectric incubator system, and the main purpose of the study is to investigate the heating performance and efficiency of the proposed system and the resistance system. Besides, other advantages of the thermoelectric system which are cooling performance, versatility, etc. are also investigated. Ultimately, since this paper is an academic study and a research focused on direct heating and cooling performances of systems, the connections added O_2 and humidifier of the AMS Amenity XP incubator were deactivated.

Table 1
Measurement uncertainties.

Variables	Uncertainty (%)
Uncertainty of volumetric rates	
Cross-sectional area where fresh air passes (A_{fresh})	2%
Cross-sectional area where mixed air passes (A_{mixed})	1.41%
Volumetric flow of fresh air ($\dot{V}_{fresh}$)	11.08%
Volumetric flow of mixed air ($\dot{V}_{mixed}$)	2.17%
Uncertainty of thermoelectric heat pump system	
Cross-sectional area of p and n type material (A)	2%
Maximum temperature difference (ΔT_{max})	0.56%
Maximum cooling power ($\dot{Q}_{c,max}$)	0.7%
Effective figure of merit (Z^*)	0.6%
Effective Seebeck coefficient (α^*)	0.87%
Effective electrical resistivity (ρ^*)	2.45%
Effective thermal conductivity (k^*)	2.89%
Resistance of TEC module (R)	3.31%
Thermal conductance of TEC module (K)	3.64%
Heating power rate of TEC modules ($\dot{Q}_h$)	1.71%
Cooling power rate of TEC modules ($\dot{Q}_c$)	6%
Power consumption of TEC modules ($\dot{W}$)	0.7%
Coefficient of performance for heating ($COP_{heating}$)	1.84%
Coefficient of performance for cooling ($COP_{cooling}$)	6.03%

Before starting to compare the performances of the systems, the hydraulic parameters of both systems should be determined according to the method in "Determination of air flow velocities and rates" section. As a result of the measurements made in the resistance incubator system, the average velocity of fresh air, the mixed air and the hood air were determined as 0.273 m/s, 1.81 m/s and 0.0929 m/s, respectively. In consequence of the calculations, the volumetric flow rate of the fresh air and mixed air were obtained as 0.001936 m^3/s and 0.004692 m^3/s. Then, by subtracting the amount of fresh air from the amount of mixed air, the volumetric flow rate sucked from the hood environment was determined as 0.002756 m^3/s. Taking into account the density of air at 25 °C, mass flow rates of the fresh, mixed and hood air were obtained 0.002293 kg/s, 0.005555 kg/s and 0.003262 kg/s, respectively. A thermoelectric heat pump system is actually a complicated system consisting of TEC module, heatsinks on the TEC module and fans on the heatsinks (Fig. 6c). In order to place the improved thermoelectric heat pump system on the AMS Amenity XP incubator, the heating element and control unit of the resistance system were removed, and the thermoelectric system developed without changing the design of the existing incubator was integrated into the AMS incubator. The created thermoelectric incubator system and the subcomponents of the thermoelectric heat pump system are shown in Fig. 6b and 6c. More detailed information about the improved thermoelectric heat pump system was given in Yeler and Koseoglu [11,12].

In this study, it was aimed to compare both systems head-to-head. So, the hydraulic parameters of the thermoelectric system should be the same as the values in the resistance system. By using Arduino, the rotational speed of the radial fan which provides air circulation of the incubator in the thermoelectric system was changed with PWM (pulse width modulation), and the PWM value which provides the volumetric flow rate of 0.004692 m^3/s in the resistance incubator system was found to be 240. While the system is operating with that PWM values, the volumetric flow rates of

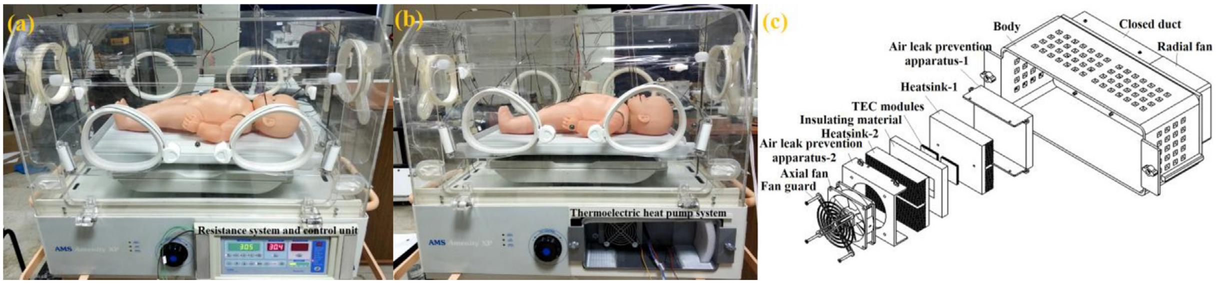

Fig. 6. AMS Amenity XP infant incubator with manikin (a) operating the resistance element (b) operating the thermoelectric heat pump [12] (c) Subcomponents of the thermoelectric heat pump system.

fresh and hood air were measured as 0.001912 m^3/s and 0.004613 m^3/s, respectively. Since the design of AMS Amenity XP incubator system is not changed, the areas where the volumetric flow rates pass through do not change as well. Thus, the velocities of the fresh, mixed and hood air were measured 0.270 m/s, 1.78 m/s and 0.0925 m/s, respectively. In this way, the hydraulic parameters of both systems were brought to the same value, and the systems were made ready to be compared with each other. Note that since there is no restriction on the other fan (axial) in the thermoelectric incubator system and heating and cooling can be done with a single device in the developed system, it has been decided to operate the axial fan at maximum PWM value (255).

The importance of the noise level in the hood for premature babies was previously mentioned in "Determination of noise level values" section, and it was expressed that the noise should not exceed 60 dB in normal operation of the incubator and 80 dB when the audible alarm in the incubator is activated [31]. The average noise levels in the hood of the resistance incubator system at the end of 90 min were measured as 49.49 dB without alarm and 58.19 dB with the audible alarm. Since the improved thermoelectric incubator system is used for academic research in this study, there are no devices that provide audible and visual warning in critical situations. Therefore, the noise level was only measured without alarm, and the average noise level in 90 min was 56.46 dB. In the thermoelectric system, two fans were run, and the modular thermoelectric heat pump system was not enclosed in a closed volume, so the noise level in the hood has slightly increased. This noise can be reduced by providing a good insulation and preferring less noise-free fans. But even in this case, the noise values of both systems are suitable because they are below the standard values.

Since resistance incubators are difficult to achieve the desired target when the air temperature inside the hood is not less than 3 °C than the ambient temperature, it is recommended to operate the resistance incubators in environments where the ambient temperature is 21–26 °C [31]. Also, in this study, since both systems were compared head-to-head the ambient temperature must be a constant value. Therefore, in all experiments, the ambient temperature was chosen as 25 ± 0.5 °C. As the incubators currently used generally operate between 30 and 38 °C, it has been decided to carry out a total of 5 experiments (without manikin) in each system according to the reference thermometer at 30 °C, 32 °C, 34 °C, 36 °C and 38 °C hood air temperature.

In an environment where the ambient temperature is 25 ± 0.5 °C, the incubator systems can bring the hood air temperatures to a steady state conditions for a maximum of 90 min in experiments without manikin which are experiments performed to investigate the thermal and hydraulic performances of the systems. In the paper, plotting data for each experiment versus time will both occupy unnecessary space and more importantly, create complexity. Therefore, all data obtained in 36 °C experiments without manikin versus time were plotted in full detail. The data in other experiments were given collectively in a single Table 2, depending on the time the mean air temperature inside the hood of the incubator systems reaches the steady state conditions. In addition, energies consumed during experiments period were added to Table 2 (see supplementary Table 2).

In 36 °C experiments without manikin, by setting the hood central temperature of both systems to 36 °C, the temperature values at each point and power consumptions of the systems were recorded instantaneously during the experiment time. Moreover, it was previously stated that temperature measurements in the hood must be made from 5 different points 10 cm above the mattress [31]. By taking the average of these values, the mean temperature in the hood was obtained (Fig. 7a). The most critical elements in both systems are undoubtedly the heating elements. Therefore, the temperatures of the mixed air absorbed from the fresh and hood environment before entering the heating elements, the surface temperatures of the heating elements and the temperatures of the mixed air after passing through the heating elements of the systems were compared separately (Fig. 7b).

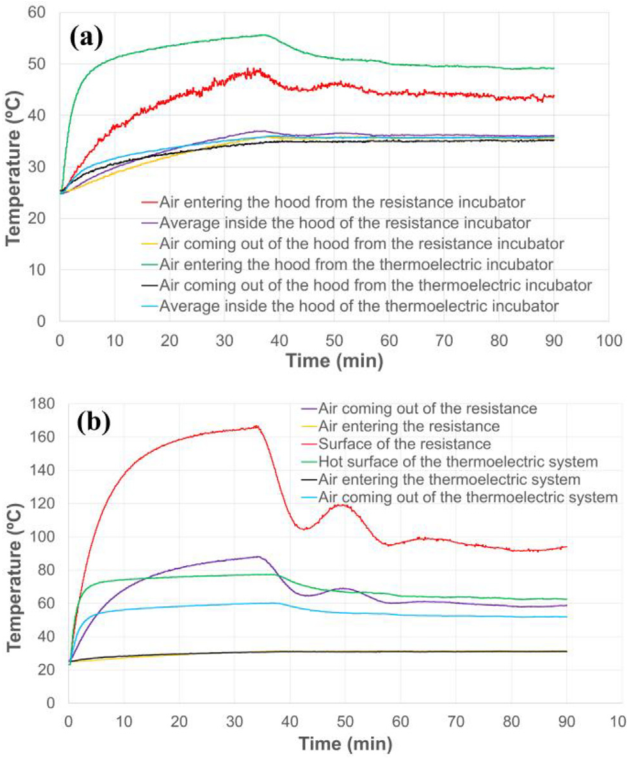

Fig. 7. Instantaneous temperatures in 36 °C experiments without manikin of the resistance and thermoelectric incubator systems (a) hood environment (b) heating element environment.

When the heating behaviors of the resistance and thermoelectric incubator system in 36 °C experiments without manikin are examined, firstly, the difference between the surface temperatures of the heating elements is noticeable (Fig. 7b). While the resistance system increased the surface temperature to maximum 164.9 °C in order to provide the desired temperature, the thermoelectric system reached 76.9 °C in the maximum condition to achieve the same target. The reason for such a difference is that the heating element of the resistance incubator cannot transfer its energy to the mixed air by convection. Because with the fin optimization performed in the thermoelectric system, mixed air passes by touching many finned surfaces (Figs. 4 and 6c) whereas it tries to do that with too few fins in the resistance system (Fig. 2). Indeed, the thermal resistances of the heating elements of both systems support the situation described above. While the thermal resistance of the resistance was calculated as 0.321 °C/W, the thermal resistance of the hot heatsink of the thermoelectric heat pump system was determined as 0.181 °C/W. In addition to all these, this high surface temperature of the electrical resistance poses a risk for both the infant and the objects around it in case of any problem. However, since the surface temperature of the hot side of the thermoelectric system does not rise to very high values, it does not pose a problem as in the resistance system.

When the mean temperature changes inside hood in 36 °C experiments without manikin are analyzed, the thermoelectric system reaches steady state at 40 min while the resistance system reaches steady state around 57 min (Fig. 7a). What is really interesting in Fig. 7a is that although the resistance system achieved the desired target by entering the hood at a lower temperature, thermoelectric system was able to achieve the same goal by entering the hood with higher temperature. The reason why the resistance system can achieve with a lower temperature is that when the resistance surface temperature rises to very high temperatures (164.9 °C at maximum condition), heat transfer by radiation also increases significantly. Since most of the parts of the AMS Amenity XP infant incubator in the lower major component are metal, it is predicted that the incubators' components are heated by radiation. The same situation is not valid in the thermoelectric system. Because the thermoelectric system cannot rise to very high temperatures (76.9 °C at maximum condition), as the electrical resistance and also provides hot air flow through a closed duct in order to prevent air leakage by design (Fig. 6c). Since the air flow takes place in the closed duct, the air temperature entering the hood is higher in the thermoelectric system. In this way, both systems achieve the same goal in different ways. In addition to all these, it has been determined in 36 °C experiments without manikin that the thermoelectric incubator controls the desired temperature with a precision of 0.05 °C, while the resistance system provides 0.1 °C. Moreover, while the maximum fluctuation of the average temperature inside the hood in the resistance system was measured as 0.8 °C, it was observed that it was measured as 0.3 °C in the thermoelectric system (Fig. 7a).

Considering the power consumed by both systems under the same conditions in 36 °C experiments without manikin, significant differences were seen (Fig. 8). Whereas the resistance system consumed a total of 1315.3 kJ of electrical energy during the experiment time, it was measured that the thermoelectric system consumes a total of 1153.3 kJ of electrical energy. The energy consumed by the thermoelectric modules during that period was determined as 953.85 kJ (see supplementary Table 2). This difference between the thermoelectric system and thermoelectric modules energies was results from by losses when converting AC voltage to DC voltage. That is why the high efficiency power supply (Mean Well LRS-350–12) was used to reduce the energy conversion losses. Since the thermoelectric modules operate like a solid-state heat pump, a total of 221.8 kJ of energy was gained from the surrounding environment through the cold surfaces of the TEC modules during the experiment time. From the measured energy values, it was simply determined that the thermoelectric system consumed 162 kJ less energy than the resistance system. If the thermoelectric system is operated directly with DC current, as in the transport incubator, since only the TEC modules consume energy, the thermoelectric system will consume 361.45 kJ less energy than the resistance system.

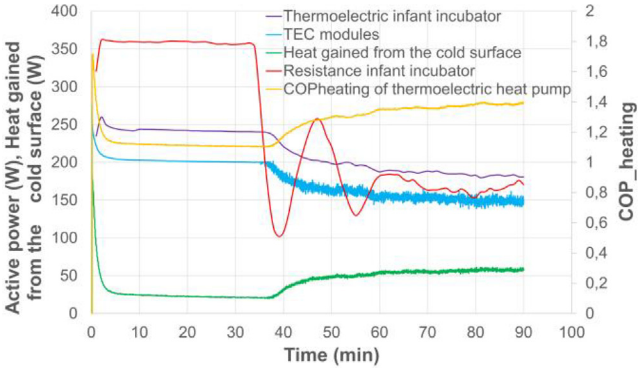

Fig. 8. Instantaneous power consumptions and $\mathrm{COP}_{\mathrm{heating}}$ (thermoelectric heat pump) changes of the resistance and thermoelectric incubator systems in 36 °C experiments without manikin.

As seen in Figs. 7 and 8, both systems become steady state after a certain period of time, and then they operate continuously with constant energy, unless a disruptive effect is made on the systems. For a healthy comparison of systems, energy values in the steady state conditions of 36 °C experiments without manikin were also compared. The resistance system reaches steady state after approximately 57 min (Fig. 7a) and consumes an average of 168 W of electrical power in the steady state (Fig. 8) whereas the thermoelectric system reaches steady state after approximately 40 min (Fig. 7a) and consumes an average of 191.78 W of electrical power in the steady state (Fig. 8). Similarly, the TEC modules consume an average of 157 W, and an average of 52.3 W of heat is gained from the cold surfaces of TEC modules. In the steady state, the resistance system consumes an average of 23.78 W less power than the thermoelectric system. If the thermoelectric system is supplied with DC voltage, as in the transport incubator, since only the TEC modules consume energy, the thermoelectric system will consume an average of 11 W less power than the resistance system.

The $COP_{heating}$ value of the thermoelectric heat pump in the thermoelectric incubator system was found to be 1.23 during the experiment time in the 36 °C experiment without manikin. However, instead of calculating the $COP_{heating}$ value of the incubator system throughout the experiment time, it is more correct to calculate the $COP_{heating}$ value after the system has reached steady state conditions. Because the incubators in practice operate for a long time in a steady state conditions unless there is a disruptive effect. As a result of experimental measurements, the $COP_{heating}$ value of the thermoelectric heat pump in the steady state was determined to be approximately 1.4 (Fig. 8). Although the thermoelectric system is a solid-state heat pump with $COP_{heating}$ value of around 1.4 in the 36 °C experiment without manikin, there are two factors that cause it to consume more electrical power than the resistance system. One of them is the loss that occurs when converting AC voltage to DC voltage, as clearly seen in Fig. 8. The other is the negative effect of PWM on the TEC modules although it is not obvious. PWM is a method that provides the voltage to be supplied to the system by switching the duty cycle on and off at high frequency.

This voltage is actually an average voltage and acts as the DC voltage obtained from a DC power supply on the system. Although this method works perfectly in many electronic applications, it is not fully compatible with the working principle of the TEC modules. Therefore, the TEC systems controlled by PWM always operates less effective than the devices that supply DC voltage directly to the system [11,37,38].

The data in Table 2 are the thermal and electrical performance values of the incubator systems when the mean hood temperatures (±0.5 °C) reach the steady state conditions. In Table 2, it is clearly seen that the thermoelectric incubator can create the mean hood temperature more quickly than the resistance incubator. At the same time, the improved system consumes less energy at each test temperature during the experimental time, and while the mean hood temperature goes from 38 °C to 30 °C, the $COP_{heating}$ value of the thermoelectric system increases because the system operates at a smaller temperature difference. In the meantime, thanks to the design of the thermoelectric heat pump system, inlet temperatures to hood are higher than the resistance system. If the existing heat losses of the infant incubator are reduced using double glass and the lower parts made of plastic materials instead of metal, the $COP_{heating}$ the thermoelectric system will increase further (see supplementary Table 2). Moreover, while the thermoelectric incubator can control the system with a very little oscillation and temperature fluctuation, resistance system can control the system with more oscillation and temperature fluctuation. In this way, the temperatures inside the hood can be maintained more stable in the thermoelectric system, and neutral thermal environment, which must be created very precisely for premature babies, can be created faster and steadily. (Fig. 9).

When the dynamic behaviors of systems are investigated through experiments with manikin, the temperature behaviors with manikin of both systems are very similar to those without babies in steady state conditions. Similarly, when the core temperature changes of the manikin are observed in both systems, small differences appeared. But that differences are not important enough to be taken into account. However, considering the times when the systems whose steady state conditions have deteriorated reach the once again the steady state, it was clearly seen that there are significant differences (Fig. 10). This proves that the improved thermoelectric incubator can meet the neutral thermal environment with fast and steady manner in all cases.

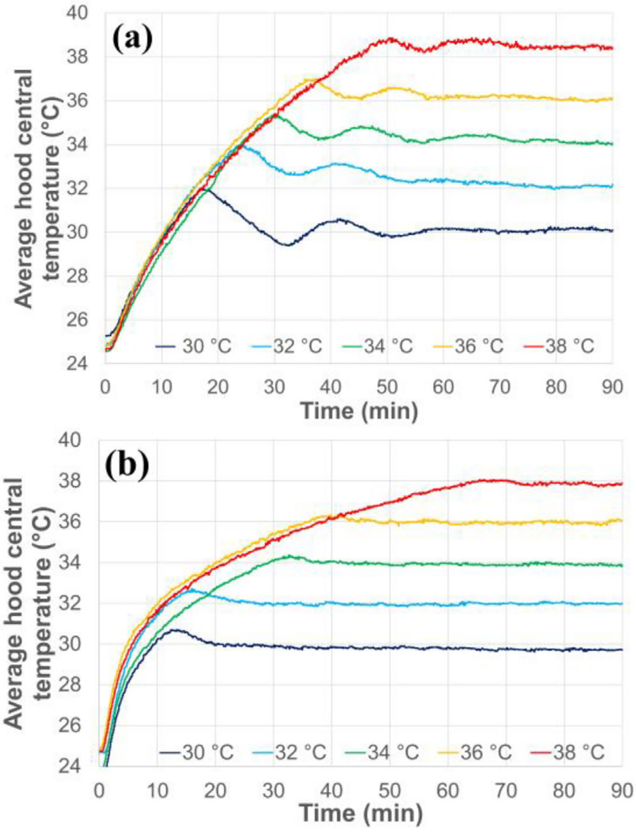

Fig. 9. Central temperature inside hood versus time (a) resistance incubator (b) thermoelectric incubator [12].

3.1. Comparison of the free cooling rate of the resistance incubator system with the cooling performance of the thermoelectric incubator system

In this paper, more attention has been given to comparing the hood heating and efficiency performance parameters of the improved thermoelectric and resistance infant incubator. In addition, the performance and effectiveness of the improved system in cooling mode, which provides an advantage to eliminate the problems and deficiencies experienced in the existing systems, were also investigated. The incubators currently used fulfill the functions of heating and humidification in case the baby only has hypothermia that is the drop of the baby's body temperature. However, if the baby has hyperthermia either a cooling blanket, which has pipes made of plastic inside and cools the baby lying on it by circulating the water or cooling agent into these pipes by means of an electronic device, is added to the resistance incubator as a second system, or the baby's body temperature is attempted to be controlled by lowering the air temperature of the resistance incubator [39,40]. As the incubator's hood is opened and closed during the placement of the cooling blanket in the incubator, fluctuations take place for a certain period of time in the set temperature and relative humidity values. On the other side, when the resistance incubator's air temperature is attempted to be lowered, the temperature may not decrease at the expected speed or the desired temperature. In this context, the thermoelectric incubator system is the best alternative for the solution of hypothermia and hyperthermia problem, which is one of the common problems in premature babies, on the same device. Because, thanks to the TEC modules used in the thermoelectric incubator, by changing only the current direction, the incubator is able to perform heating and cooling functions very quickly with a single device. In addition to hyperthermia, this method can be used to solve problems such as therapeutic hypothermia and perinatal asphyxia, which are common in premature babies.

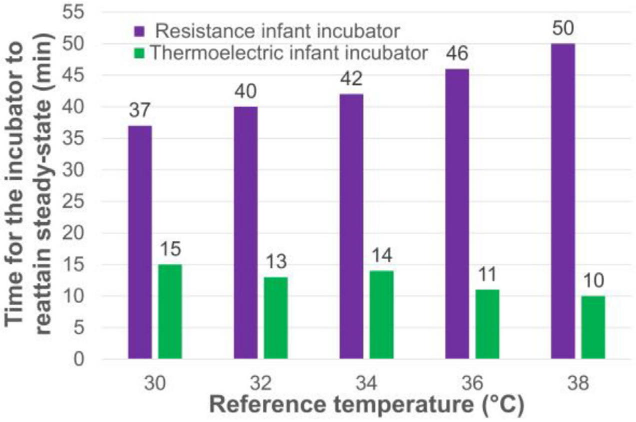

Fig. 10. Dynamic behaviors of infant incubator systems.

Cooling in the resistance incubator takes place with free convection mechanism as the surrounding environment is at a relatively lower temperature than the incubator. On the contrary, the thermoelectric incubator can operate in cooling mode by changing the current direction of the TEC module. In order to compare the cooling performance of both systems, the hood central air temperature of the systems was increased to 38 °C in an environment where the ambient temperature is 25 ± 0.5 °C. After reaching the steady state conditions in both systems, the hood central air temperature of the systems was adjusted to the ambient air, and the cooling rates from 38 °C to 30 °C were compared (Fig. 11). Whereas the center temperature of the thermoelectric system decreased from 38 °C to 30 °C in about 18 min, the center temperature of the resistance system could go down to 30 °C after approximately 58 min. It is clearly deduced from the experiment that the thermoelectric incubator is 3.2 times faster than the resistance system.

The resistance incubators are generally designed to operate in environments which an ambient temperature is range of 20–30 °C [6,31]. Since it is possible to obtain these designed temperature values in hospitals, the resistance incubators can easily operate and perform the operations expected from them. However, depending on the geographical location and climatic conditions, or when transporting the preterm baby to a technologically equipped hospital by a transport resistance incubator, the ambient temperature may be higher than the designed temperature range. In such cases, it is not possible for the resistance incubators to provide the desired temperature. On the other hand, the thermoelectric incubators are easily able to provide the desired temperature even under high the ambient temperature conditions, which they are operated in cooling mode. To investigate of the cooling performance of the thermoelectric incubators, in an environment where the ambient temperature is 25 ± 0.5 °C, the hood central air temperature was brought to 38 °C. Then, the thermoelectric system was operated in cooling mode, and by setting the hood air temperature to 20 °C, the behavior of the system was recorded (Fig. 12). Since the TEC modules are operated in heating mode before starting the experiment, it is seen that the hot surface of the TEC modules is at the temperature of 78.6 °C and the cold surface of the TEC modules is 24.8 °C at first. As soon as the thermoelectric system is operated in cooling mode, the hot surface temperature drops sharply, and the cold surface temperature raises similarly. After a short period of 7 min, the cold surface temperature reaches 75 °C, and the hot surface temperature decreases to 25 °C (Fig. 12). Since the cold and hot surfaces of the TEC modules change sharply within the first 7 min, the average air temperature of inside the hood and the mixed air temperature entering the hood decreases rapidly. Then, while the cold surface temperature of the TEC modules remains constant throughout the experiment, the temperature of the modules where the cooling process takes place continues to decrease very slowly, and the hot surface temperature decreases to 22.2 °C after 90 min. At this point, since the thermoelectric systems operate like a solid-state heat pump, the cooling power of the thermoelectric systems varies depending on the amount of heat transfer lost from the incubator and the ambient temperature. Especially in thermoelectric incubator systems operating in environments with high ambient temperatures, the cold side temperature of the TEC modules will not need to drop to 22.2 °C as in the experiment, since the ambient temperature will not drop below 30 °C. In this case, since the temperature difference (ΔT) will be less between the hot and cold surface temperatures of TEC modules, the Peltier effect determining the cooling power will be greater. Therefore, it is predicted that the thermoelectric incubator is able to achieve the desired target temperature by cooling the hood in environments with high ambient temperatures.

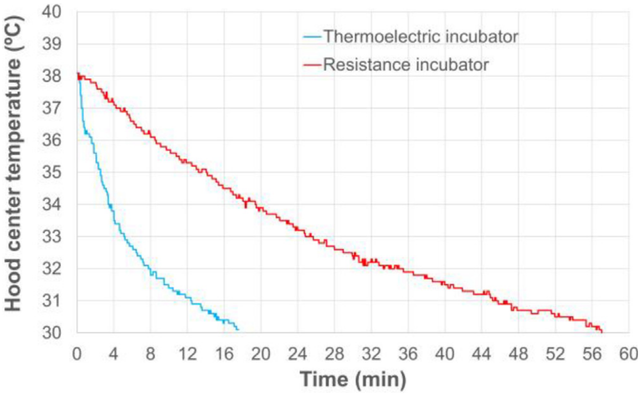

Fig. 11. Changes of cooling rates of the systems in the range of 38 to 30 °C.

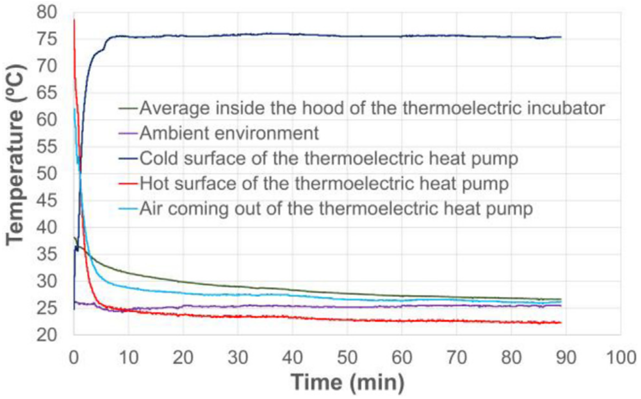

Fig. 12. Temperature changes of hot and cold surfaces of the thermoelectric system and cooling performance in an environment below ambient temperature.

In order to decrease the hot surface temperature to 20 °C in the cooling performance experiment, the heat gain from the surrounding environment of the AMS Amenity XP infant incubator was determined as approximately 71 W and the cooling power of the TEC modules in these conditions was calculated approximately 31 W. Therefore, the thermoelectric incubator operating under the specified conditions will never reach the set temperature of 20 °C (Fig. 12). As clearly stated in Yeler and Koseoglu [11], the designed thermoelectric heat pump system has improved by optimizing according to the heating mode of the hood for the limited volume, without changing the design of AMS Amenity XP infant incubator. In cases where the temperature of the cold side of TEC modules needs to be decreased, the system should be re-optimized based on the heat transfer taking place from the incubator and the desired cooling power, and this is a new study subject.

4. Conclusions

Thanks to the displacement of hot and cold surface of the thermoelectric heat pump by simply changing the current direction of the TEC modules, the temperatures that premature babies need inside the hood in hyperthermia and hypothermia health problems were created higher precisely and more homogeneously with precise control of the nano-technological TEC modules (0.05 °C for all experiments). Moreover, this has been achieved without disturbing the baby and creating any temperature and relative humidity fluctuation in the hood. In addition, when the steady state conditions of the thermoelectric incubator in any way impairs, it has been found that the thermoelectric system can create immediately the set temperature in the hood with very little oscillation and temperature fluctuation while reaching the steady state condition again. Also, it is predicted that the improved thermoelectric incubator can easily operate in any region of the world, regardless of the ambient temperature. But it should be noted that the improved thermoelectric heat pump system should be re-optimized depending on the geographical location conditions where it is used and heat transfers taking place from the incubator system. Furthermore, since the improved system is a solid-state heat pump and infant incubators are generally operated in heating mode, $COP_{heating}$ of the thermoelectric system is higher than resistance systems, especially in transport incubators which run DC voltage. In addition to all those, due to the advantage of the thermoelectric heat pump system, the system has the potential to find a solution on problems such as perioperative hypothermia, therapeutic hypothermia and perinatal asphyxia on a single device. As a result, the thermoelectric infant incubator is a good solution that can eliminate all the problems experienced in the existing resistance infant incubator systems, but other preliminary additional studies should be done in the light of this study to use this system in industrial applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jestch.2021.09.001.

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