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Knitted Multi-Functional Clothing - the Main Part of a Textile Incubator for Premature Babies

DOI: 10.5604/12303666.1201143

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Abstract
This publication presents an innovative concept for the construction of a textile incubator. A literature study was conducted concerning care for premature babies at neonatology intensive care units. Based on the physiological requirements of preterm infants, a textile incubator model was designed and manufactured. The incubator presented is composed of several layers of material. The primary function of the incubator is to maintain thermal, sensory and humidity comfort, to cool the newborn in case of programmed therapeutic hypothermia, as well as to maintain hospital sterilisation. In the first stage of work on the textile incubator we were focused on problems of the production and maintenance of heat inside the product and cooling the newborn. The most important element of the incubator construction is the heating- cooling – moistening mat, the aim of which is to deliver or receive heat from the premature baby, and to maintain adequate environmental moisture. Because the construction of the humidification mechanism is quite complicated, it is not presented in this publication. The assumed extreme values of temperatures of the functional mat are in the following ranges: for additional heating - such as stationary incubators T_{max} = 39 °C, with a precision of 1 °C; in the case of cooling in the medical hypothermia planned T_{min} = 29 °C, with a precision of 1 °C. The mat was made in the form of a 3D structure of three-layer weft knitted fabric with channels, manufactured on a cylindrical rib-knitting machine, needle gauge E20. Technological and structural parameters of the three-layer knitted mat manufactured were defined. A test stand for the analysis of heat transfer of the heating mat was designed and constructed.

Key words: *premature babies, knitted pro-medical products, textile incubator, knitted multifunctional mat, controlled microclimate.*

Purpose of using textile incubators in the care of prematurely born babies

The problem of prematurely born babies is very important for social reasons. Most premature babies are born in African and Asian countries- about 85%. However, the problem of prematurity is also observed in highly developed countries, such as the US, where it reaches 12.3% [1]. In Poland, every year 300 000 babies are born prematurely, of which 5.5% are infants with a birth weight below 2 500 g. Common causes of premature birth are medical factors e.g.: infections, hypertension, diabetes or defects of the fetus. Non-medical reasons are, among others, stress, hard work, maternal age, and living conditions [2]. Prematurely born infants are not able to maintain proper body temperature as their subcutaneous adipose tissue is not sufficiently formed, and their muscles are too weak to produce heat. Problems with the regulation of body temperature and disturbances in the economy of water and electrolyte arise due to the small amount of fat tissue. In the case of infants born on time, brown fat enables the production of large quantities of heat and ensures a proper body temperature, but in the case of premature babies this process is disrupted. The heat balance of an adult is equal to zero, but in the case of premature babies it is negative [3]. The skin of infants born prematurely before 25 weeks of pregnancy is adapted to aquatic life, and does not fulfill any of the protective functions. It is very thin, being of about 27.4 microns, of gray or brown color, and the stratum corneum and sebaceous glands are not well developed - virtually non-existent. The lack of the stratum corneum results in increased moisture loss, and therefore after birth premature infants are temporarily placed in polyethylene bags. The baby rapidly losses water and heat through the skin by evaporation, radiation, convection and conduction, as a result of temperature difference between the body and the surrounding environment [4]. The conduction process is the loss of heat to objects which are in direct contact with the child's body e.g. a mattress, quilt or clothing. Convection is heat loss to the surrounding air, depending on the difference between the body temperature of the newborn and ambient temperature, the size of the body surface exposed, and the speed of air movement [5]. Here radiation means the reflection of heat from the skin to surrounding cold surfaces, also depending on the temperature difference. One of the most important ways of heat loss is evaporation. Under physiological conditions, 20% of thermal energy is lost in that way, and in situations of increased demand for heat loss (fever, high temperature of the environment) it can rise to 65%. As a result of evaporation, skin temperature can drop by 3˚C within a few minutes after birth. Evaporation is much higher in the case of premature newborns than that of mature babies, and may be larger than the total heat production [6]. Common causes of heat loss by preterm babies are as follows:

- A high adverse relation of the body surface area to the weight in relation to the possibility of producing thermal energy,
- Limited stocks of metabolic substrates,
- A thin layer of subcutaneous fat as well as poorly developed muscles and other tissues involved in thermal insulation which do not provide an adequate barrier against heat loss,
- The small diameter of the body makes that the volume of ambient air is less than for the diameter of an infant body born at the proper time,

***Figure 1.** a) Open incubator [10], b) closed incubator [Photo taken by the authors].*

- Infants with reduced muscle tension are not capable of adopting the bent position, which could help to reduce the body surface exposed to heat loss [7].

The consequences of disturbances in thermal management are hypothermia, hyperthermia, apnea and stress of the newborns caused by cold. These are the most common complications resulting from placing premature babies in unsuitable thermal conditions. Therefore in order to protect the babies against excessive heat and moisture loss they are placed in incubators, which are used to maintain a stable environment with controlled temperature, humidity and oxygen concentration [8]. The control and regulation of skin temperature involves programing the temperature of the skin on the control panel of the incubator (target value), and then comparing it with the actual temperature of the skin of the premature newborn measured by a skin temperature sensor. This temperature can be maintained in the range from 34.0 to 37.0 °C. Air temperature control is performed by programing the temperature of the air (target value) and comparing it with the actual temperature. Air temperature can be maintained in the range from 20.0 to 37.0 °C. Incubators are also equipped with a built-in humidifier, allowing air humidification in the range from 30% to 95% of relative humidity (RH). Humidity is controlled with 1% accuracy. The temperature in the incubator depends on the temperature of the infant after birth, which on average equals 37 - 37.5 °C [9]. The temperature in the incubator is 35 °C, which corresponds to the internal temperature of the mother's body. Humidity is set in the range from 60% to 90%. Newborns lying in incubators are often connected to specialised medical equipment which supports their life functions and takes over the functions which were previously performed by the mother's body. Premature infants require constant body temperature. Therefore most premature babies spend the first few hours or days of their lives in bed, over which a heat source is fixed. This is the so-called open incubator (***Figure 1.a***), with a heater called a heat radiator [10], which heats the baby and helps maintain a constant, proper body temperature. The sensor of the open incubator, attached to the baby's skin, monitors skin temperature, and the incubator regulates the heat. Another type of incubator is a closed incubator (***Figure 1.b***) [11], which is a transparent box made of plastic. Such an incubator is a closed cubicoid protecting the child from sudden changes in air temperature. The activities that doctors and nurses perform around the child take place through oval holes in the walls of the incubator or by lowering one of its walls. The closed incubator is equipped with a heating system [12]. In some cases it is connected to a sensor attached to the skin of the newborn; heating is regulated depending on the temperature of the baby's body. Incubators are also equipped with screens which display the temperature and other necessary data [13].

Incubators are equipped with many additional devices supporting medical care for newborn babies. One such device is a respirator, which assists breathing. If the child does not need the help of a respirator, but is not quite ready to breathe independently, it can wear nasal cannulas, thanks to which CPAP is maintained. CPAP is a method of respiratory support used in the treatment of sleep apnea as well as in the case of respiratory failure [14]. Other devices monitoring the vital functions of newborns are cardiac and respiration monitors, devices for measuring blood pressure, oximeters and monitors of carbon dioxide. One of the most important devices to which the child is typically connected all the time while staying in a neonatal ward is a monitor of heart activity and breathing [15]. Incubators are also equipped with devices for administration of drugs and food. In order to protect premature babies against microorganisms incubator are disinfected at a temperature of 110 °C and the remaining water is removed from inside the machine [16]. In the literature, we found only one publication relating to the design and material solution for a textile portable [17]. The main reason for the implementation of a portable incubator were the high prices of maintenance and purchase of stationary incubators [17]. This problem is observed not only in the United States but also in developing countries. The portable incubator was made of a polyamide fabric,equipped with a bag filled with a wax substance which kept heat inside the product.

Figure 2. Sleeping bag -portable incubator by Embrace and the way of placing a container with the heating package inside the product [18].

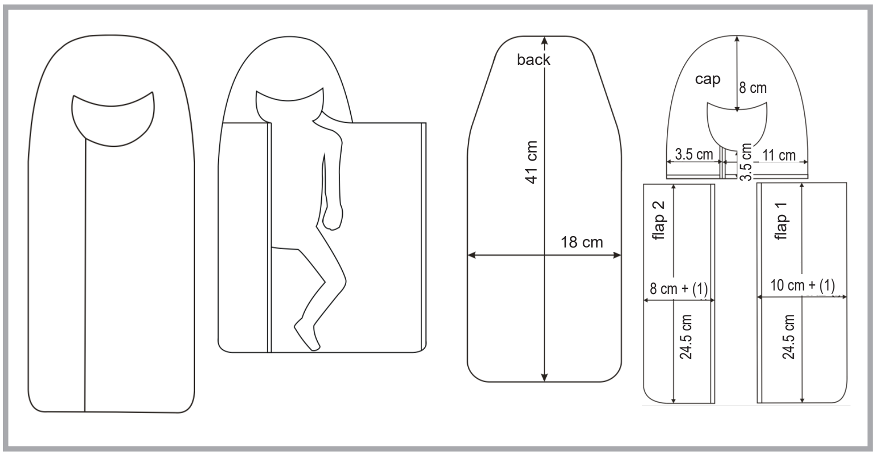


Figure 3. Design of a textile incubator for prematurely born infants.

The package is heated in an electric heater, or in the case of a power failure, in warm water for 20 minutes. The heating substance keeps heat inside the incubator from four to six hours. Such incubators can be used both at home and in hospitals, as well as a means of transport for infants. ***Figure 2*** shows a sleeping bag -portable incubator by Embrace [18].

Analysis of existing methods of caring for preterm infants, including the construction of the incubator, was supposed to enable the transferring of some characteristics of the existing equipment onto the construction of a new textile incubator.

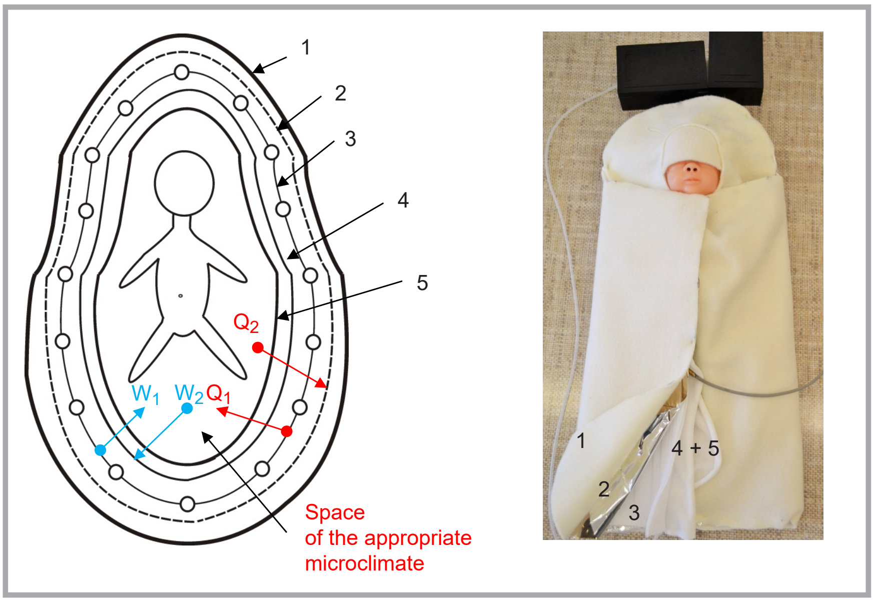


Figure 4. Model of designed textile incubator for preterm babies [Photo taken by the authors].

Construction assumptions for a textile incubator for preterm infants

In order to justify the construction assumptions adopted for the textile incubator, the following research works were undertaken:

1. Analysis of the physiology of prematurely born children on the basis of a literature study and direct observation of medical care which preterm infants received at the Department of Neonatology of the Polish Mother's Memorial Hospital- Research Institute in Lodz.
2. Interviews with the medical community and nursing staff concerning medical requirements for the construction of the textile incubator designed. At a meeting with the medical staff of PMMH in Lodz, an original design of a functional model with temperature and moisture control allowing for hypothermia was presented. The model of the incubator consisted of several layers of material, combining the properties of thermal insulation, moisture barrier, textile heater, as well as an inner sensory layer directly adjacent to the child's skin. The problems of material stiffness, fasteners and exposing parts of the product presented were also discussed. Prof. Ewa Gulczyńska, head of the Department of Neonatology of PMMH in Lodz welcomed the solution proposed. According to Professor Gulczyńska, this solution can be especially useful in the following areas of medical care for premature infants:

- Transport of new-borns qualified for thermal hypothermia (medical emergency services - transport of newborns in an ambulance)
- Protection of the newborn in the first twenty-four hours of life,
- Infants requiring surgery (proper coverage of the operating field). During the operation the child is heated while lying on his or her back,
- An important function which existing stationary incubators and portable textile incubators do not have is that of cooling during the planned medical hypothermia,

- The possibility to performing an X-ray and ultrasound radiation without removing the baby from the incubator.

The incubator presented was placed in a baby carrier. According to the medical personnel, the carrier is not suitable for carrying an infant, but may be used for storing the external parts of the incubator e.g. the control panel of electrical devices controlling the patient's vital functions. Another problem is the construction of the incubator in the aspect of sterilisation. Maintenance requirements (sterilisation) of the textile incubator determine the modular construction of the product.

It is expected that some elements of the product will be disposable e.g. the internal cover, the "pillowcase", made of a soft fabric coated with a vapour permeable membrane, which the newborn will come into direct contact with. The construction of the textile incubator resembles a "cocoon". A medical phantom of a premature baby showing its silhouette on a 1 : 1 scale was used for the design and execution. This model also reproduces skin structure, enabling the choice of appropriate materials for the internal structure of the textile incubator. The technological design of the incubator is shown in ***Figure 3***.

The incubator model presented in ***Figure 4*** consists of five layers of materials, labelled with numbers from 1 to 5. The first outer layer (1) is an insulating layer made of a knitted-fabric with low thermal conductivity. For this layer a knitted fabric of plush polar stitch can be used, as well as a picking up woolen knitted fabric or spacer fabric with aerogel. Layer (2) is made of a metallised polyester film constructed in such a way that the internal side of the incubator is in silver colour. Functional active layer (3) is a heating - cooling – moistening mat. Layers 1, 2 and 3 are immovable and perform a heat-insulating function, as well as that of temperature and humidity regulation inside the textile incubator. Layer (4) is a vapor permeable membrane attached to layer (5) - "soft" fabric made of organic cotton or textured polypropylene. The function of the vapour-permeable membrane is to preclude the penetration of liquids and bacteria from the newborn's body to the inside of the incubator. Thus the membrane transmits moisture and heat from the inside of the incubator to the child's body. Layers (4, 5) are disposable-replaceable parts which will be replaced every 2 or 3 days, according to the suggestions of the main doctor. Figure Q1 stands for heat supplied from the active functional mat in the range from 37 to 40 °C, Q_2 - heat reflected from the skin of the newborn, W_1 - moisture supplied from the heating-moistening mat in the range from 50 to 90%, and W_2 for moisture lost by the child's skin. The values of $Q_1 \approx Q_2$ and $W_1 \approx W_2$ are approximately constant. ***Figure 5*** shows a prototype of the textile incubator. The construction of the incubator also provides a soft velcro - type fastening or zip made of plastic.

Figure 5. *Photograph of a prototype of the textile incubator for preterm babies [Photo taken by the authors].*

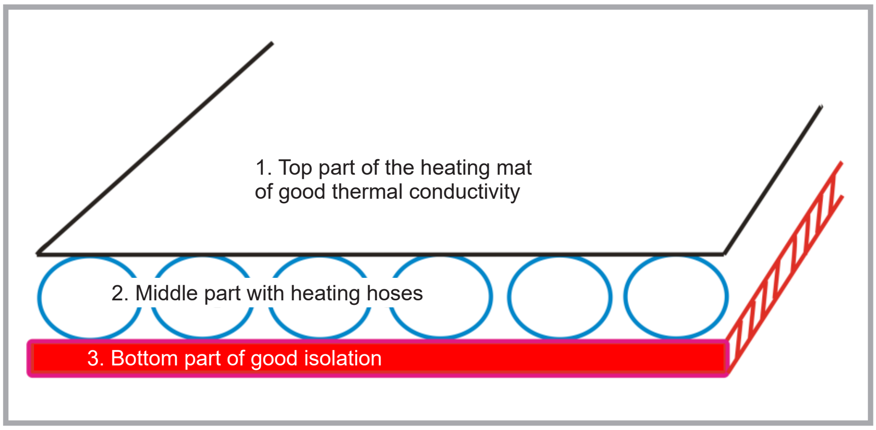


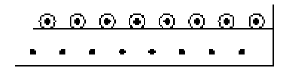
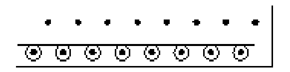
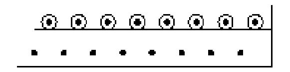
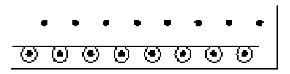
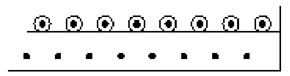
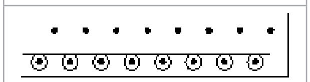
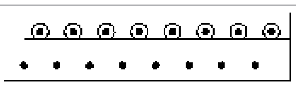
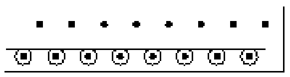
Figure 6. *Diagram of the knitted channelled mat [Photo taken by the authors].*

Structure and technology of a knitted channelled mat

The first stage of the study focused on the problems of producing and maintaining heat inside the textile incubator, so that the heat balance of the premature baby equals zero. For this purpose a knitted channelled mat was introduced into the incubator and filled with hoses of liquid passing through the heating element. The medical community rejected the concept of the heating element of the incubator in the form of an electrical heating mat. Doctors emphasised that the child cannot be placed in an electromagnetic field produced by current flowing in the mat. In addition, a resistance heater not only would expose the infant to the influence of the electric field but would create a very large design problem because of the need to work at very low voltage. Thus the mat was made in the form of a three-layer weft-knitted channeled fabric on a cylindrical rib-knitting machine, needle gauge E20, with the following machine settings:

- Take-up: connecting monofilament of the needle of 4.79 mm, combining courses of 3.17 mm
- Of the needle, channeled systems of the needle of 3.34 mm.
- Strain: take-up threads - 4 cN, monofilaments- 3.1 cN,

Table 1. Stitches of the channeled fabric.

Nr	Stroke direction	Stitch	Disc/ Cylinder	Stitch name	Remarks
1	×2		T C	Plain stitch on the needles of the disc	Binding-off course.
				Plain stitch on the needles of the cylinder.	
				Cardigan stitch on the needles of the disc and cylinder.	
				Plain stitch on the needles of the disc	
				Plain stitch on the needles of the cylinder	
				Cardigan stitch on the needles of the disc and cylinder.	
2	×4		T C	Plain stitch on the needles of the disc	Links width.
				Plain stitch on the needles of the cylinder	
3	×7		T C	Plain stitch on the needles of the disc	Channells width.
				Plain stitch n the needles of the cylinder	

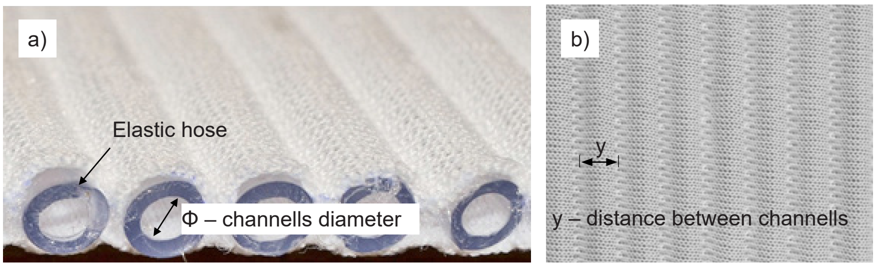


Figure 7. *a) cross-section of the knitted heating, b) knitted channelled mat, top view [Photo taken by the authors].*

- Distance between the disc and cylinder: 2.85 mm.

The mat was made in variants of the following raw materials: polypropylene threads of 84 × 25 tex × 2 "SZ", polyester threads of 83 dtex × 2, polyester threads of 116 dtex, polypropylene monofilament with a diameter of 0.08 mm, and bamboo threads of 20 tex (BAMBOO®). The concept of the mat construction derives from the nature of its thermal conductivity. The external layer of the mat has a small cover factor and high thermal conductivity, while the internal layer has a higher cover factor and lower thermal conductivity. A scheme of the channeled mat is presented in ***Figure 6***. A plastic hose of a diameter of 5 mm and wall thickness of 1 mm, made of PVC, with a thermal conductivity of 0.17 W m^{-1}×K^{-1} was introduced into the channels of the mat, and heated distilled water was passed through it. Ultimately it is planned to introduce into the mat a more flexible silicone hose with higher thermal conductivity of 0.24 W m^{-1}×K^{-1}.

The mat was designed in such a way that after introducing the hose into the channels it remains flexible, since it is a part of active clothing with a thermoregulatory function. Inside the textile incubator one heating zone of constant temperature was assumed, because the medical community rejected the concept of multi-zone heaters of different temperatures. In addition, inside the incubator the child will be monitored for body temperature by temperature sensors, which will directly affect the temperature regulation of the textile incubator. In the description of the construction of the heating - cooling - moistening mat no mechanism of humidification of the air inside the incubator was reported, which was done deliberately because it is a very complex problem, and will be addressed in a separate publication. In this article we were only focused on the function of the heating - cooling mat. ***Table 1*** illustrates a schematic record of stitches of the channelled knitted fabric.

Figure 7 illustrates the channelled knitted fabric produced with a tube introduced into the channel. The channel's diameter and distances between them are indicated.

The channeled mat size 30 × 50 cm has the following parameters: weight of the mat without the tube: 27.31 g, weight of the mat with the tube: 285.04 g, thickness of the mat without the tube: 2.15 mm, thickness of the mat with the tube: 6.44 mm, course density of the knitted fabric: Pr = 154 cm r/10, wale density of the knitted fabric: Pk = 109 c/10 cm, surface mass of the fabric Mp = 182.1 g/m^2, loop width A = 0.92 mm, loop height:

Table 2. Heat-insulating properties of component materials of the textile incubator.

Nr	Tested object	Thermal conductivity $\lambda \times 10^{-3}$, $Wm^{-1}K^{-1}$	Thermal diffusion $A \times 10^{-6}$, m^2s^{-1}	Thermal absorption b×1, $Wm^2s^{-0,5}K^{-1}$	Thermal resistance $r \times 10^{-3}$, $W^{-1}Km^2$	Sample thickness h×1 , mm	Flux ratio of maximum and stationary heat, P	Stationary flux ratio at the contact point q, KWm^2
1	Fleece	0.044	0.713	42.8	0.074	3.27	2.17	0.231
2	Channelled fabric	0.049	0.753	57.4	0.059	2.98	1.16	0.601
3	Cotton fabric	0.039	0.129	110	0.014	0.57	1.16	0.601
4	Polypropylene fabric	0.043	0.086	148	0.014	0.61	1.48	0.781

B = 0.65 mm, loop shape factor C = 0.71, diameter of the channels Φ = 5 mm, and distance between the channels y = 2 mm. Additionally a study of the thermal insulation of the materials used in the construction of the textile incubator was carried out on Alambeta device [19]. The values obtained are presented in ***Table 2***.

The data given in ***Table 2*** show that the materials used to construct the textile incubator have low coefficients of thermal conductivity λ in the range of 0.039 - 0.49 $Wm^{-1}K,^{-1}$ and thus possess good thermal insulation properties. Thermal insulation properties of the materials depend on their thickness. The results presented in the table show that the thickest fabrics are the knitted plush fleece fabric, h = 3.27 mm, and the channeled knitted fabric, h = 2.98 mm.

Design of a stand for analysing the temperature distribution of the heating mat

The next stage of work on the textile incubator was the design and execution of a test stand for analysing the heat transfer of the heating mat. This stand consists of a Dräger incubator, Isolette C 2000, three peristaltic pumps with controllers, four four - channel thermometers (16 measurement sites), a hytherograph measuring the temperature and humidity inside the incubator, and liquid heating equipment. The test stand constructed was placed inside the incubator, and the knitted channeled mat was placed inside the device. A significant feature of the construction of the heating mat is that it can perform two different functions: heating – T max = 39 °C, with a precision of 1 °C, just like in stationary incubators, and cooling - in T min = 29 °C, with aprecision of 1 °C in the case of planned therapeutic hypothermia, which is a new characteristic of a textile incubator. A schematic draft of the stand for analysing the temperature distribution of the heating-cooling – moistening mat is shown in ***Figure 8***. In the construction of the test stand there are valves 'z_i', which may direct the liquid flow in the tubes in two directions: towards the heating element 'g' in order to heat the liquid, or towards the refrigerator 'ch_i' in order to cool it. ***Figure 9*** presents a photograph of the test stand constructed.

Firstly tests were carried out of the temperature distribution of a heating mat

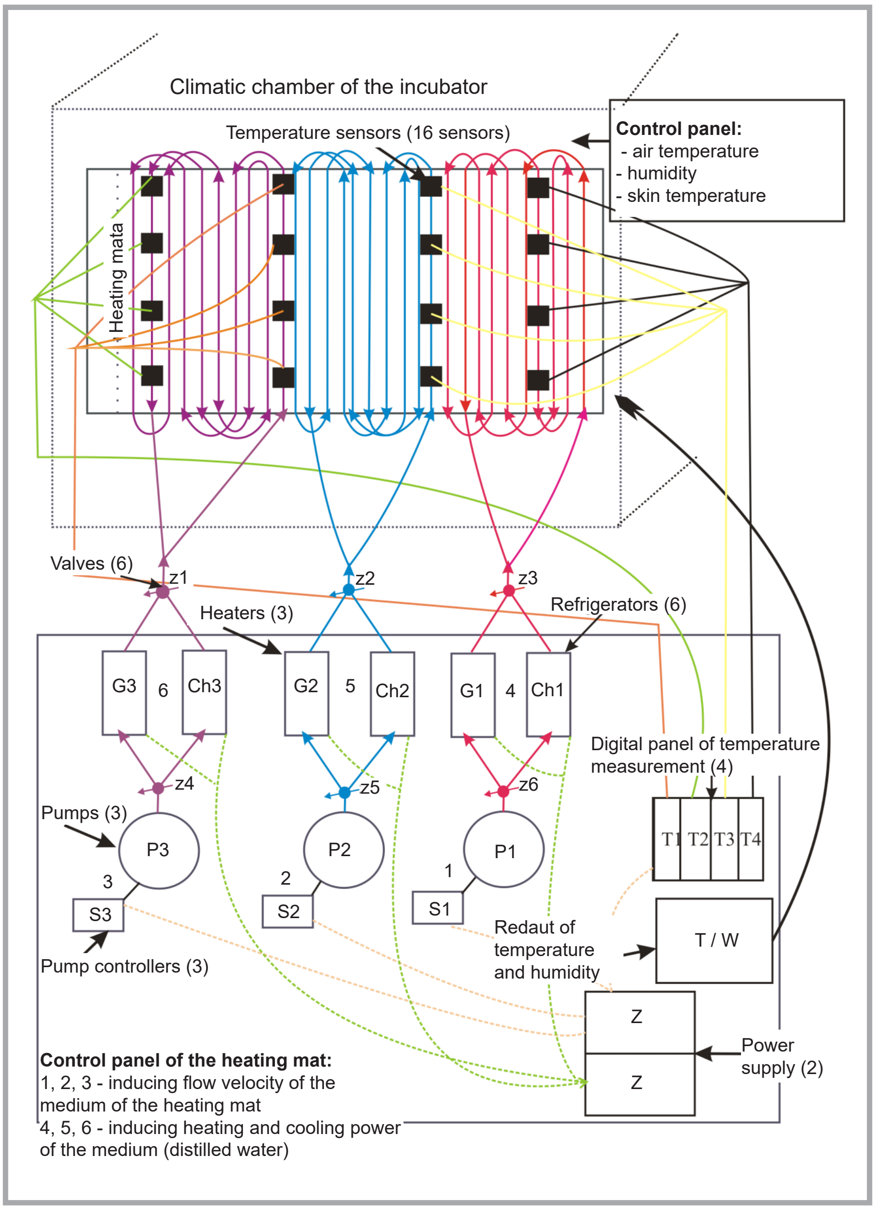


Figure 8. *Diagram of the test stand for measuring heat emmited by the heating mat [Photo taken by the authors].*

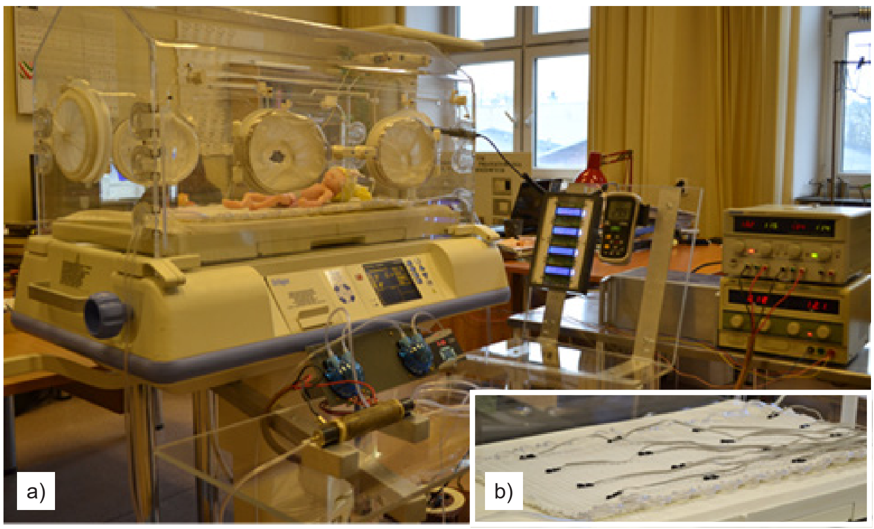


Figure 9. *a) test stand for identifying the heat flux emitted by the heating mat, b) knitted mat with temperature sensors [Photo taken by the authors].*

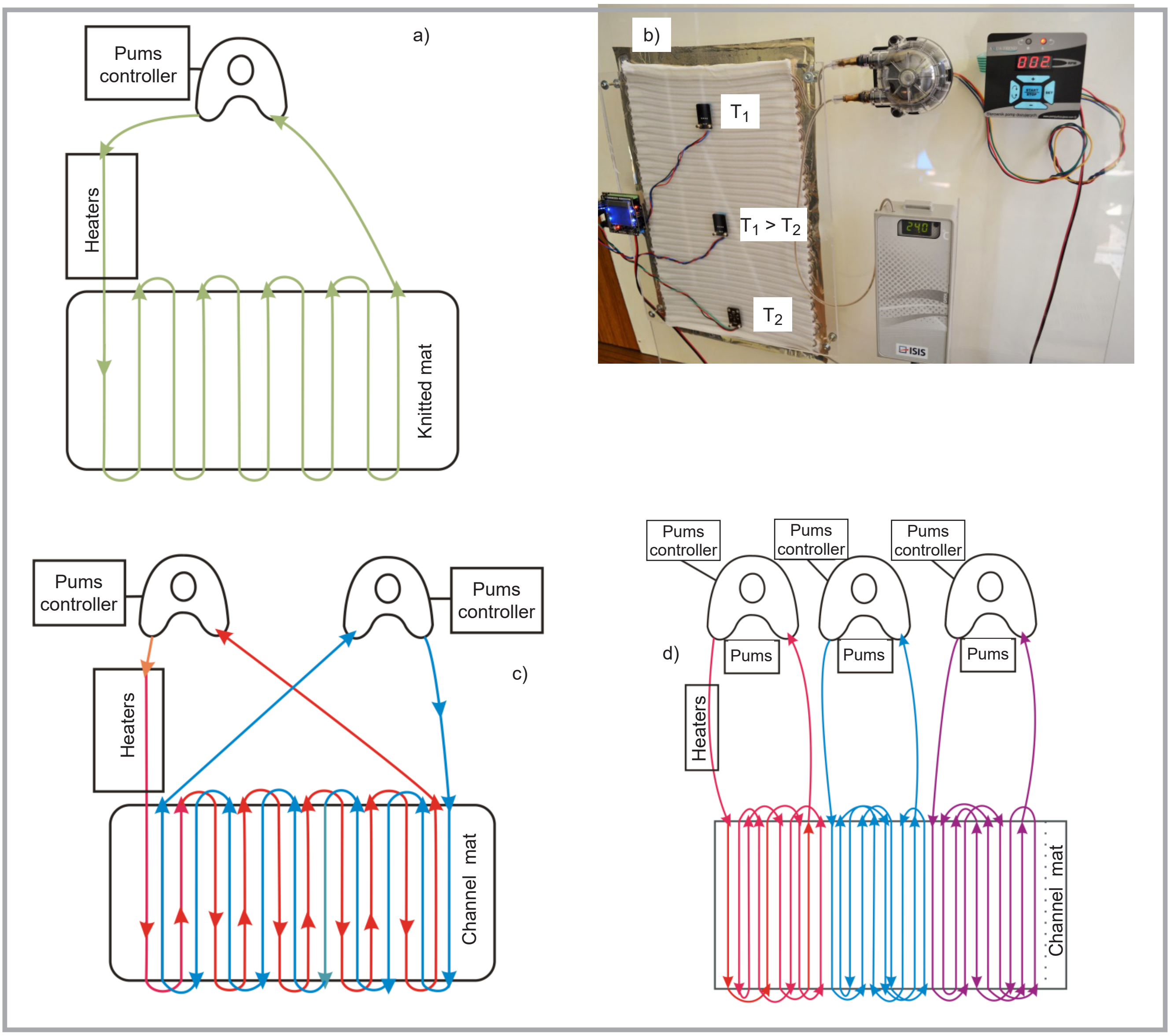


***Figure 10.** a) Diagram of a mat with one heating zone, b) photo of a mat with one heating zone, c) diagram of a mat divided into two heating zones, d) diagram of a mat divided into three heating zones [Photo taken by the authors].*

with one interlaced hose to obtain a single heating zone. After the test, it turned out that the input temperature T1 = 25.3 °C is higher than the output temperature T2 = 23.5 °C, with the temperature difference equalling 1.8 °C. The aim of the project was to maintain constant heat distribution over the entire surface of the mat, and for this purpose two variants of interlacing the hose in the mat were elaborated. In the first solution a hose of a diameter of 5 mm was introduced into the channels of the mat of a width of 7 courses and distance of four courses. The mat was divided into two heating zones. The second solution was to use a mat of a width of channels equal to 9 courses and to introduce a hose of the same diameter.

The mat was divided into three heating zones. The hose was divided into short segments of 30 cm, which were connected by a flexible tube of smaller diameter at every fourth channel. ***Figure 10*** shows a diagram of individual variants of hose interlacing through the mat. Ultimately the heating medium will be introduced into the mat by a separate collector supplying individual heating tubes, while reception of the heating medium will be realised by a parallel receiving collector.

Results of the analysis of the heat flux emitted by the heating mat and the construction of the temperature thermoregulation system inside the incubator will be presented in the next publication.

Conclusion

1. From the medical point of view, the textile incubator can be used in the following areas of medical care for premature newborns:
   - The transport of newborns qualified for thermal hypothermia (medical rescue services- transport in an ambulance)
   - Protection of the newborn in the first twenty-four hours of life,
   - Transport from the delivery room to a neonatal unit,
   - Infants requiring surgery (appropriate cover of the operating field); during the operation the child will be heated while lying on its back,

- Cooling function in the planned medical hypothermia,
- The possibility to perform an X-ray and ultrasound radition without removing the baby from the incubator.

2. In order to protect the newborn from loss of heat and humidity, a textile incubator was designed. The primary function of the textile incubator is to maintain a proper microclimate inside the product. The second function will be cooling of the newborn in the case of planned hypothermia treatment. The textile incubator consists of five layers of material. The first two layers provide a thermal barrier (a textile thermos). The third layer is a system of active heating - cooling – moistening mats. Another two layers are disposable- interchangeable elements composed of a vapour-permeable membrane combined with a sensory knitted fabric.
3. Materials selected for the elements of the incubator have low coefficients of thermal conductivity and thus good thermal insulation properties. In the first stage, the study focused on the problem of keeping heat inside the textile incubator, so that the heat balance of the preterm baby equals zero.
4. The most important element of the construction of the textile incubator is the heating- cooling mat, whose aim is to deliver or receive heat from the baby's body. For this purpose, three-layer weft-knitted channeled fabric was manufactured on a cylindrical rib-knitting machine, needle gauge E20. Technological and structural parameters of the three-layer knitted mat produced were defined.
5. A hose of a diameter of 5 mm was introduced into the channels of the mat. The heating mat was designed in such a way that it remains flexible even after introducing the hose into its channels. A schematic diagram of temperature control and heat flux emitted by the mat for a multi-variant way of arranging the hose with the heating – cooling medium was presented.
6. A test stand was designed and constructed for analysis of heat transfer of the heating mat. It consisted of a Dräger incubator, Isolette C 200, three peristaltic pumps with controllers, four four - channel thermometers (16 measurement sites), a hytherograph measuring the temperature and humidity inside the incubator, and liquid heating equipment
7. At the current stage of research, analysis was made of temperature distribution and the amount of heat emitted by the heating – cooling mat as a function of flux velocity and temperature of the heating mat medium. Results of the analysis will be presented in subsequent publications.

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Received 13.08.2015 Reviewed 07.12.2015