Disponible en ligne sur
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com

IRBM

IRBM 35 (2014) 189–201

Original article

Building simulation model of infant-incubator system with decoupling predictive controller

M.A. Zermani *, E. Feki , A. Mami

Laboratoire de recherche en automatique, École nationale d'ingénieurs de Tunis (ENIT), University Tunis el Manar, BP 37, Le Belvédère, 1002 Tunis, Tunisia

Received 19 February 2013; received in revised form 1st July 2014; accepted 7 July 2014
Available online 26 August 2014

Abstract

This paper introduces theoretical modelling working on the thermal behavior of the premature infant. This study aims at developing a model useful for the prediction and design of the appropriate controller in objective to reduce evaporative heat loss. A calculation code has been developed to simulate the thermal response of a premature baby to climatic solicitation inside the incubator system. The model allows us to take into consideration radiative, conductive, convective, and evaporative heat transfers inside the incubator system. The air temperature and the humidity rate, which play a salient part in the convective and evaporative exchanges, are calculated by a coupled transfer function. At present, the environmental conditions (temperature and humidity) inside incubator are controlled with a classical Proportional Integral Differential (PID). In this work, we proposed a decoupling Generalized Predictive Controller (DGPC) based on the model described below to achieve an optimal thermal conditions (36.5–37.5) for immature newborn infants (birthweight <1000 grams). Real and simulations results prove the feasibility and effectiveness of the proposed model and controller.

1. Introduction

Generally, preterm neonatals are not capable of keeping constant their body temperature. This means that they have immature thermal regulation systems and their mechanisms for heat production are under-developed. Therefore, some form of external thermoregulatory support is important. The first use of incubators for the premature neonatal was in 1722. Tarnier (Parisian obstetrician) [1] adapted the idea of using chicken incubators to take care of premature infants. Since that time, the incubator industry has witnessed a great development and by 1896 the basic configuration of incubator design was completed and still considered as the basis of today's incubators. The incubator process is used to produce healthful micro-environment in order to reduce newborn heat loss by controlling temperature inside incubator. Temperature is one of the most important factors that need to be maintained with a minimum variation. But temperature control alone is not sufficient to provide comfortable environment. Therefore, the relative humidity control is also very important to reduce the newborn heat loss [1–3]. Many authors [4–7] observed a 40% reduction in evaporative losses when the relative humidity increases from 20 to 60%. After the observation of Blackfan and Yaglou on newborns of low weight, it is recommended to maintain humidity levels inside the incubator at 65–70%. Many works have demonstrated that the survival rate of preterm infants cared for in incubators increases when warmer environment conditions are provided [4–6]. Moreover, providing a neutral thermal environment is essential for premature infants during the first month of life. This is mainly due to very high evaporative losses resulted by large skin surface area. The premature infants are raised in closed incubators in which the thermal conditions should be those of the thermoneutrality. This environment is defined by the International Union of Science as an area of ambient temperatures in which the value of metabolism is minimal while maintaining the internal temperature of the body at a constant and normal level (36.5 to

* Corresponding author.
E-mail address: Aymen_net@voila.fr (M.A. Zermani).

http://dx.doi.org/10.1016/j.irbm.2014.07.001
1959-0318/

Nomenclature

A_{net}	Area of the mattress not covered by the infant, m^2
A_r	Surface area of the neonate's local segment normal to the incubator walls, m^2
A_s	Surface area of skin in contact with the mattress, m^2
A_{wi}	Surface area of the incubator walls, m^2
bf	Blood flow rate parameter, sec^{-1}
C_{pa}	Specific heat of air, $J.kg^{-1}.°C^{-1}$
C_{pb}	Specific heat of the blood, $J.kg^{-1}.°C^{-1}$
C_{pc}	Specific heat of the core, $J.kg^{-1}.°C^{-1}$
C_{pm}	Specific heat of moist air, $J.kg^{-1}.°C^{-1}$
C_{ps}	Specific heat of the skin, $J.kg^{-1}.°C^{-1}$
C_{pw}	Specific heat of the wall, $J.kg^{-1}.°C^{-1}$
$Evap$	The evaporation loss from the skin of the infant to the environment, mL/kg/day
h_{acv}	Heat transfer coefficient for forced convection, $W.m^{-2}.°C^{-1}$
h_{cvo}	The convective heat transfer coefficient for free convection, $W.m^{-2}.°C^{-1}$
hfg	Latent heat of the water, $J.kg^{-1}$
IV	Inspired second volume, mL/kg × sec
K_C	Thermal conductivity of the core, $W.m^{-1}.°C^{-1}$
K_{mat}	Thermal conductivity of the mattress, $W.m^{-1}.°C^{-1}$
m	Mass of the infant, kg
M_c	Mass of the core, kg
M_{rs}	Resting metabolic rate at the thermoneutral zone for the 1st week of life, W/m^2
M_s	Mass of the skin, kg
M_w	Mass of the wall, kg
Q_{acv}	Rate of convective heat transfer between incubator air and incubator wall, watt
Q_{bc}	Rate of convective heat transfer between core and skin via blood, watt
Q_{cd}	Rate of conductive heat transfer between core and skin, watt
Q_{cvo}	Rate of convective heat transfer between incubator walls and environment, watt
Q_{ic}	Rate of conductive heat transfer between mattress and incubator body, watt
Q_{lat}	Rate of latent heat energy due to breathing, watt
Q_{mat}	Rate of convective heat transfer between incubator air and mattress, watt
Q_{mc}	Rate of conductive heat transfer between skin and mattress, watt
Q_{met}	Rate of metabolic heat production of the core, watt
Q_{sen}	Rate of sensible heat energy due to breathing, watt
Q_{ro}	Rate of radiation heat transfer between incubator walls and environment, watt
Q_{scv}	Rate of convective heat transfer between skin and incubator air, watt
Q_{se}	Rate of evaporative heat transfer between skin and incubator air, watt
Q_{sr}	Rate of radiation heat transfer between skin and incubator wall, watt
S_a	Surface area of the local body segment, m^2
T_a	Air temperature, °C
T_c	Core temperature, °C
T_{ex}	Exhaled air temperature, °C
th_m	Mattress thickness, m
T_m	Mattress temperature, °C
T_s	Skin temperature, °C
T_w	wall temperature °C
V_{cb}	Blood volume, mL
w_a	Humidity ratio of the inhaled air
w_{ex}	Humidity ratio of the exhaled air
ρ_a	Air density, kg/mL
ρ_{bl}	Blood density, kg/mL
ρ_c	Core density, $kg.m^{-3}$
ρ_{h2o}	Water density, kg/mL
σ	Stefan-Boltzmann constant, 5.64×10^{-8} $W/m^2.K^4$
ε_s	Radiant emissivity of the skin, assumed to be 1.0
ε_w	Radiant emissivity of the wall_Plexiglass

37.5 °C) [6]. To regulate precisely the air temperature and relative humidity and to discuss the evaporation loss, it is absolutely essential that the model of infant incubator should be precise for prediction but also simple to control. Most authors have limited their investigation to a model useful for prediction; Ultman [20] developed a simulator of neonatal energy transfer to provide a convenient and precise comparison of sensible heat loss in incubator. Wheldon [21] also studied the radiant and convective heat loss from a baby in an incubator using manikin. Leblanc [5] described the fundamental equations involved in thermal exchange between infants and their environment. Simon [16] developed a theoretical model of infant incubator dynamic for the analysis of the factors that influence neonatal thermoregulation.

The aim of this study is how to succeed in developing a model useful for the prediction and for the design of the appropriate controller intending to reduce evaporative heat loss. For this reason direction, the model of a newborn infant and the climate control in incubator have been developed and described. To simplify, we decomposed the process in two models. The first model was developed to characterize the coupled energy in a dynamic regime and water vapor balance of the premature infant. This model is based on physical and biological equations developed by Simon [16]. It incorporates conduction, convection, evaporation, radiation, and heat generation from the infant in terms of metabolic rates [8,9]. The second model, based on an empirical and statistical approach that uses both input and output data, is developed to control the environmental condition incubator.