Simulation of Circulation Module

F. Solc[1,2], **I. Vesely**[1,2], **and F. Zezulka**[1,2]

[1]Department of Control and Instrumentation, FEEC
Brno University of Technology, Technicka 12, Brno, Czech Republic
[2]Centre for Research and Utilization of Renewable Energy, FEEC
Brno University of Technology, Technicka 12, Brno, Czech Republic

Abstract— Presented paper offers a description of a lung nutrient circulation model and its regulation. This circuit is currently being developed and it is a part of a project dealing with the transportation of lungs. Lung tissue is very sensitive and it loses its quality in a few hours without nutrition. When lungs are being transported, the transportation time has to be short, otherwise nutritional system must be used. In that case there are two conditions that must be complied. Firstly we need to keep the lung in a required temperature. The second condition is to keep the required pressure. The whole system was expressed by equations and modeled in Matlab Simulink for a better control design of the real model.

1. INTRODUCTION

Circulation module is designed for nutrition of lungs during transport [1]. The organs that are meant to be used for transplantation or ex-vivo experiments [2] must be handled with careduring transportation, so as to avoid irreversible damage that would disable transplant [3]. Lungs have to be transported with the same caution even if they are used only for experiments [4, 5]. Currently, circulation modules for longer vitality of organs are being developed, which means that the time of transporting can be longer. These circulation modules must match certain requirements. In our case, these requirements are a constant flow and a constant temperature of the liquid.

The controlled system consists of several parts. The most important one of them is the reservoir where the nutrient fluid is stored and heated. From this reservoir a liquid is piped in tubes through the pump into the lungs and consequently back into the reservoir. The flow intensity of the nutritional liquid is determined by the speed of the pump that ensures a constant liquid flow in the lung.The circuit includes a feedback control, and several temperature sensors for providing a constant fluid temperature (Fig. 1). Detailed description of the entire system is described in [6].

The article discusses the equations used for creation of the model and the created model itself. Various verification tests of sensors of this model are carried out. The proposed controller performs temperature control in specific limits.

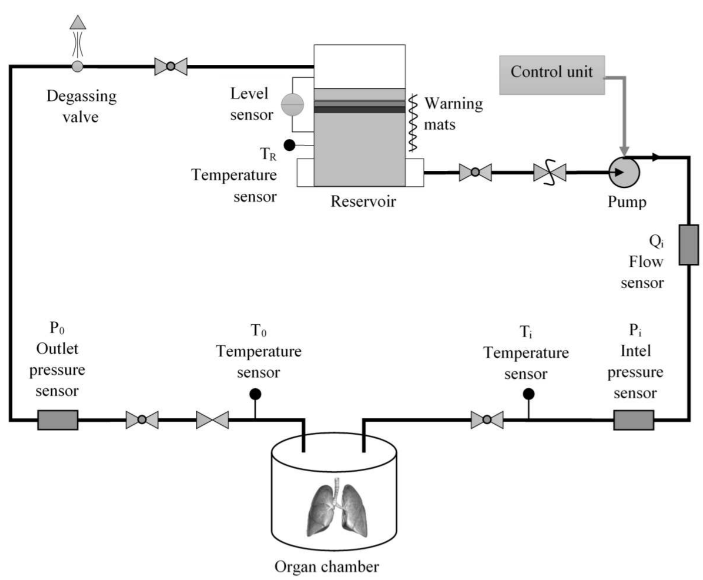

Figure 1: Principial scheme of the thermal model.

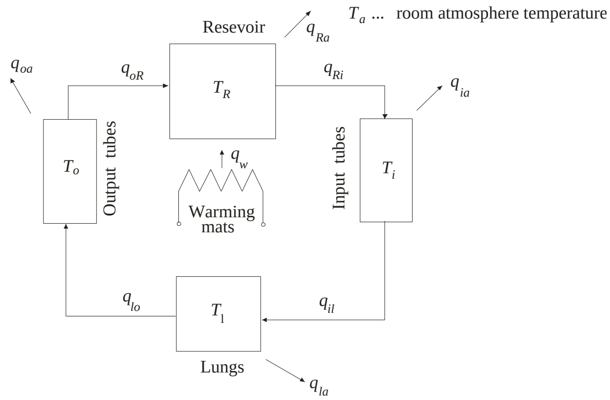

Figure 2: Principle scheme of the thermal model.

2. MATHEMATICAL MODEL OF THE THORACIC BOX

We suppose that the thermal part of the MCM can be described as a system of vessels shown on Fig. 2 [6].

The temperature of nutritional fluid in the lung must be constant. This temperature is changing due to different temperature of external atmosphere in different parts of the system. The liquid transfers the heat through the pipes into the lungs. Than it is piped back to the reservoir where it is being warmed.

Heat transfer is characterized by heat flux q. The following equations characterize heat transfer

$$cm_R \frac{dT_R}{dt} = q_w + c\rho Q \left(T_0 - T_R\right) - \left(\frac{T_R - T_a}{R_R}\right) \tag{1}$$

$$cm_i \frac{dT_i}{dt} = c\rho Q \left(T_R - T_i\right) - \left(\frac{T_i - T_a}{R_i}\right) \tag{2}$$

$$cm_l \frac{dT_l}{dt} = c\rho Q \left(T_i - T_l\right) - \left(\frac{T_l - T_a}{R_l}\right) \tag{3}$$

$$cm_o \frac{dT_o}{dt} = c\rho Q \left(T_l - T_o\right) - \left(\frac{T_o - T_a}{R_o}\right) \tag{4}$$

where the denote c is a specific heat capacity of the perfusion liquid [$\mathrm{Jkg}^{-1}\mathrm{K}^{-1}$], q is the heat flux [W], m is the mass of nutrition liquid in the specific vessel [kg], ϱ is the density of perfusion liquid [kgm^{-3}], Q is the volumetric flow of perfusion liquid [$\mathrm{m}^3\mathrm{s}^{-1}$], T is the temperature [K], R is the thermal wall resistance of the specific vessel [KW^{-1}]

Equations (1)–(4) can be rewritten into state variable form

$$\frac{dT_R}{dt} = \left(\frac{\rho Q}{m_R} + \frac{1}{cm_R R_R}\right) T_R + \frac{\rho Q}{m_R} T_o + \frac{1}{cm_R R_R} T_a + q_w \tag{5}$$

$$\frac{dT_i}{dt} = \left(\frac{\rho Q}{m_i} + \frac{1}{cm_i R_i}\right) T_i + \frac{\rho Q}{m_i} T_R + \frac{1}{cm_i R_i} T_a \tag{6}$$

$$\frac{dT_l}{dt} = \left(\frac{\rho Q}{m_l} + \frac{1}{cm_l R_l}\right) T_l + \frac{\rho Q}{m_l} T_i + \frac{1}{cm_l R_l} T_a \tag{7}$$

$$\frac{dT_o}{dt} = \left(\frac{\rho Q}{m_o} + \frac{1}{cm_o R_o}\right) T_o + \frac{\rho Q}{m_o} T_l + \frac{1}{cm_o R_o} T_a \tag{8}$$

Input variables: q_w is the control variable heat flux from warming matts, T_a is the disturbance ambient temperature.

Output variables (see Fig. 1): T_R is the temperature inside the reservoir (measured), T_i is the temperature in the input tubing (measured), T_l is the temperature inside the lungs (not measured), T_o is the temperature in the output tubing (measured).

Equations (5)–(8) can be written in more compact form

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{9}$$

where

$$\mathbf{x} = [T_R \quad T_i \quad T_l \quad T_o]^T \qquad \mathbf{u} = [q_w \quad T_a]^T \tag{10}$$

$$\mathbf{A} = \begin{bmatrix} -\left(\frac{\rho Q}{m_R} + \frac{1}{cm_R R_R}\right) & 0 & 0 & \frac{\rho Q}{m_R} \\ \frac{\rho Q}{m_i} & -\left(\frac{\rho Q}{m_i} + \frac{1}{cm_i R_i}\right) & 0 & 0 \\ 0 & \frac{\rho Q}{m_l} & -\left(\frac{\rho Q}{m_l} + \frac{1}{cm_l R_l}\right) & 0 \\ 0 & 0 & \frac{\rho Q}{m_o} & -\left(\frac{\rho Q}{m_o} + \frac{1}{cm_o R_o}\right) \end{bmatrix} \tag{11}$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{cm_R} & \frac{1}{cm_R R_R} \\ 0 & \frac{1}{cm_i R_i} \\ 0 & \frac{1}{cm_l R_l} \\ 0 & \frac{1}{cm_o R_o} \end{bmatrix} \tag{12}$$

Matrix form can be used for calculation of equilibrium steady state where $\mathbf{x} = \mathbf{x}_0 = \mathbf{const}$ and $\mathbf{u} = \mathbf{u}_0 = \mathbf{const}$.

$$\mathbf{x}_0 = -\mathbf{A}^{-1}\mathbf{B}\mathbf{u}_0 \tag{13}$$

This is used for the conversion to the required power of heating mats.

E.g., with parameters that are given bellow with the power of heating matts to be 100 W at ambient temperature 20°C Equation (13) fields steady state temperatures $\mathbf{x} = [23.41\ 22.65\ 22.58\ 22.50]^T$.

3. REALIZATION OF CONTROLLER

The lung should have a constant temperature during transportation. However as mentioned above, thermal losses occur in the circulation module and the nutritional liquid must be heated constantly.

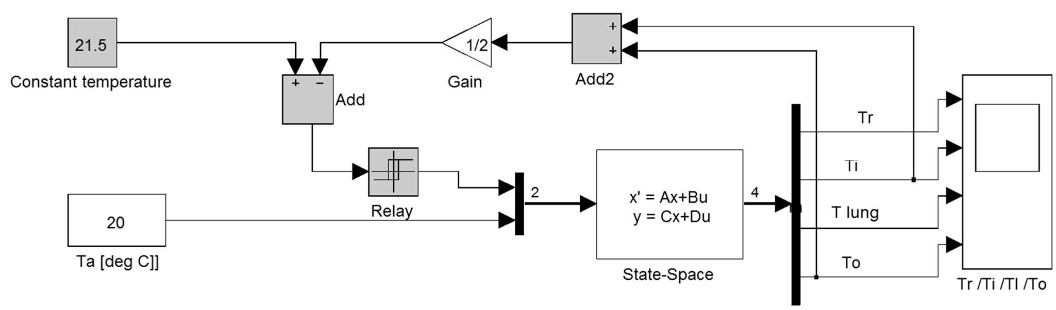

Figure 3: Simulation scheme of the thermal system.

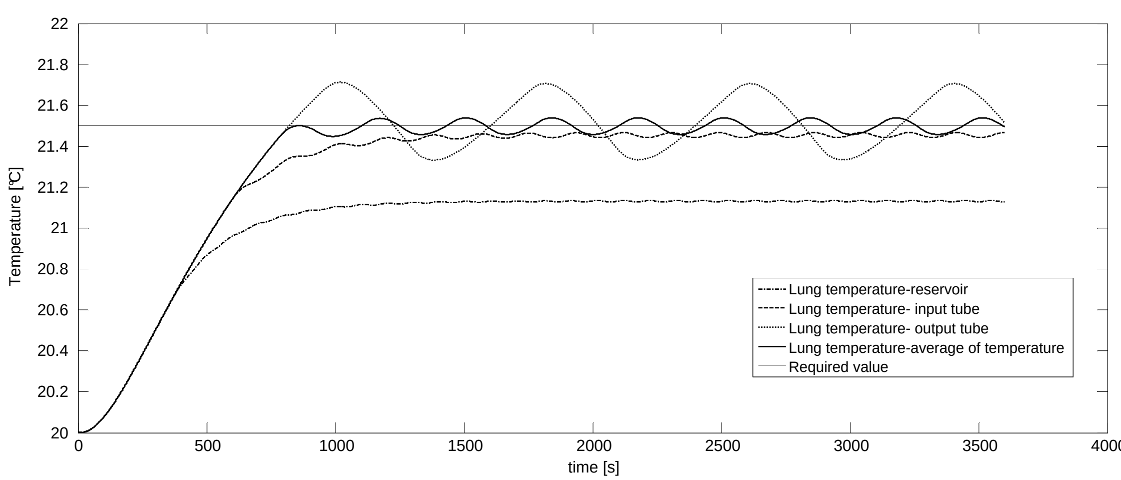

Figure 4: Temperature controls with different places of temperature measurement.

A hysteretic switch on/off with feedback is used for temperature control and data for this controller are used from temperature sensors. Therefore, the system is equipped with several temperature sensors located in the reservoir and in the input and output tubes. The temperature in the lungs is not measured.

The model consisting of the equations described earlierwas used for testing various ways of control. The aim of the test was to determine the places where it is necessary to scan the temperature and how many sensors are needed for the control. The temperature of lung was controlled to 21.5°C, the hysteresis was 0.1°C. and four options of control were tested.First one: the temperature is measured in the reservoir. Second one: the temperature is measured in the input tube. Third one: the temperature is measured in the output tube. And the fourth one: the mean value of temperatures in input and output pipes is used as output temperature.

In the Figure 3, we can see the model with the control system, where the temperatures are averaged.

4. CONCLUSIONS

The time of organ transport and possible physiological changes of these organs during transport sometimes complicate the work with this material. Therefore, circulation modules are being developed to improve the transporting process. In our case it is a circulation module for the lung. The problem dealt with in the article was related to heating of the nutritional liquid and to keeping the temperature constant. The simple relay regulator with hysteresis was selected to keep the temperature within certain limits. For a simple control, the circuit is equipped with several temperature sensors which are located in the reservoir and in the tube close to the lung, but no sensor is located in the lung. The model of circulation module was created for controller testing and for the selection of correct sensors combination. As the graph shows measuring of temperature in only one reservoir is insufficient due to thermal losses. The best method is averaging data from the sensor in the tubes in front of and behind the lung.

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