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Numerical analysis of whole-body cryotherapy chamber design improvement

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Abstract. Whole body cryotherapy is a state-of-the-art method that uses cold for treatment and prevention of diseases. The process implies the impact of cryogenic gas on a human body that implements in a special cryochamber. The temperature field in the chamber is of great importance since local integument over-cooling may occur. Numerical simulation of WBC has been carried out. Chamber design modification has been proposed in order to increase the uniformity of the internal temperature field. The results have been compared with the ones obtained for a standard chamber design. The value of temperature gradient in the chamber containing curved wall with certain height has been decreased almost twice in comparison with the results obtained for the standard design. The modification proposed may increase both safety and comfort of cryotherapy.

1. Introduction
The positive effect of cold in medicine has been known since early times; however, new cold therapy methods are continuing to develop. In various ancient cultures, cold agents such as snow and ice-water mixtures were used to treat a wide range of diseases [1]. Nowadays, an up-to-date method called whole-body cryotherapy (WBC) is widely applied for cold therapy. WBC takes place in a cryogenic chamber or cabin in the atmosphere of extremely cold gas (from -110 to -140°C), the exposure continues from 1 to 3 minutes [2-3]. Cryochambers typically have an automatic control systems allowing the adjustment of treatment conditions such as: temperature, gas velocity and humidity. It was shown that cryochambers are easier to use and less expensive compared to the cryocabins [4].

A research of cryotherapy benefits is extensive. A short review of some papers is presented further. There are three main fields in which WBC aspects are most commonly studied: sports activities, health and wellbeing. The influence of WBC on psychological and physiological health has been studied in [5-9]. One of actual WBC issues is to measure a temperature of skin during the therapy. Theoretical analysis of skin temperature and heat losses were performed in [10]. Factors associated with sex should be considered when choosing the operating modes of the cryochamber. The impact of human sex on the thermoregulation process after the WBC has been studied in [11-12]. Women-participants experienced a more intense decrease of skin temperature than male counterparts.

An analysis of temperature fields within the cryochamber is of great importance. Due to an inhomogeneous distribution of gas temperature within the cryochamber, there is the risk of local integument over-cooling [3]. Gas distribution uniformity depends on inlet temperature, velocity and chamber design. This paper studies temperature field within the cryochamber and how the design factor influences it.
2. Simulation model
A mathematical model of WBC was implemented using the finite element method (FEM). The modelling was carried out in the COMSOL Multiphysics software using the parameters of the cryochamber “KRION Standard” (Russia). Many cryogenic gases are used in WBC, for the modelling presented in this paper, nitrogen N₂ was used. The model was considered as time-dependent. A scheme is shown in Fig. 1. The mesh consisted of 44200 domain elements of triangular shape and 6979 boundary elements.

The mathematical model included a system of differential equations describing heat transfer and laminar flow.

A general heat equation for a fluid (in N₂ gas) [13]:

\[ \rho C_p \frac{dT}{dt} + \rho C_p \cdot \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_p + Q_{vd}, \]

where \( \rho \) - density, \( C_p \) - heat capacity, \( T \) - absolute temperature, \( t \) – time, \( \mathbf{u} \) - velocity vector, \( \mathbf{q} \) - heat flux, \( Q \), \( Q_p \), \( Q_{vd} \) - heat sources.

The heat flux density:

\[ \mathbf{q} = -\kappa \nabla T, \]

where \( \kappa \) – a coefficient of thermal conductivity.
Term $Q_p$ takes into account an additional heat source due to a thermoacoustic effect and term $Q_{vd}$ includes an additional heat released from a viscous dissipation. However, these two effects can be neglected due to their insignificance [13].

A general heat equation for a solid (in a cryochamber volume):

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \mathbf{q} = Q,$$

(3)

The solution for a single-phase liquid-gas flow is based on Navier-Stokes equations [14].

The equations of motion for a single-phase fluid are the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

(4)

and the momentum equation:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \left( \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{I} \right) + \mathbf{F}.$$  

(5)

For simplicity, the authors assumed that fluid has a constant density [15]; thus, equation (4) is reduced to:

$$\rho \nabla \cdot \mathbf{u} = 0,$$

(6)

and equation (5) becomes:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p \mathbf{I} + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \mathbf{F},$$

(7)

where $\mathbf{F}$ - volume force vector, $\mu$ - dynamic viscosity, $\mathbf{I}$ - identity matrix.

The flow of cryogenic gas was described using the dependences of gas temperature and velocity on time (Table 1). These parameters were used as boundary conditions applied to the inlet 2 (fig.1). Gas passed from the outlets 1 and 3; temperature in the outlets equaled to 298 K and pressure equaled to 0 Pa. There were no viscous effects and boundary layers on the interfaces between gas and cryochamber elements. This condition was described as: $\mathbf{u} \cdot \mathbf{n} = 0$, where $\mathbf{n}$ is normal vector.

Convective heat transfer was used to describe heat exchange between the cryochamber free boundaries and the environment [16]:

$$-\mathbf{n} \cdot \mathbf{q} = q_0$$

(8)

$$q_0 = h \cdot (T_{\text{ext}} - T),$$

(9)

where $h$ - heat transfer coefficient ($h = 2 \text{ W/(m}^2\text{K})$), $T_{\text{ext}}$ - external temperature ($T_{\text{ext}} = 293 \text{ K}$).

$\text{N}_2$ properties are presented in Table 2. The cryochamber material has the following properties: $\kappa = 0.04 \text{ W/(m} \cdot \text{K})$; $\rho = 80 \text{ kg/m}^3$; $C_p = 1470 \text{ J/(kg} \cdot \text{K})$.

| time (s) | T (K) | u (m/s) |
|---------|-------|---------|
| 0       | 298   | 0.2     |
| 12      | 140   | 20      |
| 180     | 140   | 20      |
| 200     | 298   | 0.2     |
### Table 2. \( \text{N}_2 \) properties used in the simulation

| \( T \) [K] | \( \rho \) [kg/m\(^3\)] | \( C_p \) [J/(kg\(\cdot\)K)] | \( \kappa \) [W/(m\(\cdot\)K)] | \( \mu \) \( \times \)10\(^5\) Pa\(\cdot\)s |
|---|---|---|---|---|
| 100 | 3.65 | 1038.88 | 0.0091 | 0.6580 |
| 150 | 2.44 | 1039.01 | 0.0137 | 0.9806 |
| 200 | 1.82 | 1038.98 | 0.0181 | 1.2774 |
| 250 | 1.46 | 1039.12 | 0.0222 | 1.5483 |
| 300 | 1.21 | 1039.71 | 0.0258 | 1.7806 |
| 350 | 1.04 | 1041.06 | 0.0291 | 2.0065 |
| 400 | 0.90 | 1043.75 | 0.0323 | 2.2064 |

3. Analysis of temperature field during WBC

During the WBC analysis several designs including the standard one were considered (fig. 1). The height of chamber wall and its profile were adjusted. The uniformity of temperature field was studied. Figure 2 shows the standard distribution of an average temperature (avg \( T \)) in the chamber volume (curve 1). The modifications proposed haven’t shown a significant change of avg \( T \) (curves 2-7). Maximum difference in values of avg \( T \) among all the modifications does not exceed 20 degrees.

However, a temperature gradient decreases dramatically as a result of wall modification (fig. 3). The use of the wall with the curved profile and height \( h_w = 1700 \) mm (fig. 3, curve 7) allows the reduction of temperature gradient by 100 K/m.

It can be seen that the most intensive cooling takes place at \( t = 20 \) s. Figure 4 shows a detailed picture of temperature distribution in different planes of the chamber volume at this moment of time.

**Figure 2.** A time-dependent distribution of an average temperature in the volume of cryochamber. 1 - standard wall; modified wall with the height \( h_w \): 2 - \( h_w = 400 \) mm, 3 - \( h_w = 500 \) mm, 4 - \( h_w = 800 \) mm, 5 - \( h_w = 1100 \) mm, 6 - \( h_w = 1400 \) mm, 7 - \( h_w = 1700 \) mm.
Figure 3. Time dependence of temperature gradient absolute value in the volume of the cryochamber. 1 - standard wall; modified wall with the height \( h_w \): 2 - \( h_w = 400 \) mm, 3 - \( h_w = 500 \) mm, 4 - \( h_w = 800 \) mm, 5 - \( h_w = 1100 \) mm, 6 - \( h_w = 1400 \) mm, 7 - \( h_w = 1700 \) mm.

Figure 4. Temperature field distribution. 1) the camber with the standard wall (longitudinal section), 2) the chamber with the modified wall (longitudinal section, \( h_w = 1700 \) mm); results were obtained at the time moment equaled 20 s.

A – cross-section corresponding to the half of the chamber height; B - cross-section corresponding to the chamber height.

4. Conclusion
The distribution of temperature field seems to depend on gas velocity and trajectory. In order to make it more uniform, a design modification including a curved wall with an enlarged height has been
proposed. Such modification allows a noticeable decrease of temperature gradient. This result is of crucial importance since a high temperature difference decreases treatment safety and may cause local over-cooling of human body that is rather hard to detect. Smoother \( \text{N}_2 \) flow may improve comfort of the therapy and allow possible exposure increase. The results obtained seem to be dependent on gas temperature, inlet velocity, inlet and outlet dimensions and other parameters that can be an object of further research.

5. Conflict of interest
The authors declare that they have no conflict of interest on the content of this paper.

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