Radiation heat transfer between human and cryocabin walls

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Abstract. The paper considers the particular case of intensive radiation heat transfer in the system consisting of a human body and cryocabin walls of cryosauna. Calculations for three models have been made, namely, human-vertical wall, which is arranged parallel to a human, human-vertical wall, which is positioned at a certain angle, and a human-cryoc Furna. Analytical calculations are compared with Ansys-based numerical calculations. The impact of radiation heat transfer in this radiation-convective heat transfer problem is estimated. Conclusions are drawn about taking into account the radiation heat transfer and a rational method for calculating this heat transfer problem.

1. Introduction
The role of radiative heat transfer is important both in processes taking place at high temperatures and those characterized by an essential temperature difference. In cryosaunas, where the cooling process occurs due to supply of liquid nitrogen, the air temperature can reach 77-78 K, the wall temperature can reach 120-140 K, while the human temperature is higher than 273.15 K. The system consisting of human and walls of the cryoc Furna is characterized by radiation-convective heat transfer. This is one of the most difficult cases of heat transfer when the equations of radiant energy transfer are solved together with the equations of motion and convective heat transfer [1-7]. The problem of radiation-convective heat transfer cannot be solved analytically, while for a numerical solution, it is necessary to make several assumptions. Therefore, for practical calculations, the principle of independence of convective and radiative heat transfer is used. Also, radiative heat transfer can be used to improve heat transfer processes in cryosaunas, confirming the relevance of this study [8, 9]. In this paper the impact of radiation heat transfer is considered. The objective of this research is to create a simplified method for calculating radiation heat transfer based on the average temperatures of heat transfer surfaces and to calculate radiation heat transfer between a human and the walls of a cryoc Furna.

2. Materials and methods

2.1. Calculation cases and assumptions
Three calculation cases are considered in this paper:
Case 1 – human - vertical wall, which is arranged parallel to human;
Case 2 – human - vertical wall, which is positioned at an angle;
Case 3 – human - entire cryoc Furna.

The base of the cryoc Furna heat exchange surface is made in the form of a regular hexagon with a side of 511.5 mm. The height of the cryoc Furna heat exchange surface is 1501 mm (Figure 1).
The following assumptions are made in the model:
1. A person is presented as a simplified geometric model;
2. Convective heat transfer caused either by a difference of surface temperatures or by the radiant flux absorption is not taken into account. Convective heat transfer due to a temperature difference is an independently calculated function that goes beyond the limits of this paper. Convective heat transfer due to the radiant heat flux absorption is neglected since the convective medium of the calculation model is mainly composed of optically transparent monatomic gases (O\textsubscript{2} and N\textsubscript{2}).
3. The temperature of the outer wall over the entire surface is kept constant;
4. The temperature of a human over the entire surface is kept constant;

2.2. Analytical calculations

The radiative heat transfer model is described by the system of equations (1).

\[
\begin{align*}
Q_{1,i,j} &= \sigma_0 \cdot T_i^4 \cdot F_i \cdot \varepsilon_i, \\
Q_{2,i} &= Q_{2,i,j} + Q_{2,i,\text{air}}, \\
Q_{2,i,j} &= \sigma_0 \cdot T_j^4 \cdot H_{ij} \cdot \varepsilon_j, \\
Q_{3,i} &= Q_{2,i} \cdot (1 - \varepsilon_i)
\end{align*}
\]

where $Q_{1,i,j}$ is the heat emitted from human or wall, $W$; $Q_{2,i}$ is the total heat falling on human or wall, $W$; $Q_{2,i,\text{air}}$ is the heat falling on human or wall from the air, $W$; $Q_{2,i,j}$ is the heat falling on human from the wall, or from the wall on human, $W$; $Q_{3,i}$ is the reflected heat from human or wall, $W$; $T_i$ is the temperature of human or wall, $K$; $F_i$ is the surface area of human or wall, $m^2$; $\varepsilon_i$ is the degree of blackness of human or wall; $\sigma_0$ is the Stefan-Boltzmann constant; $i, j$ are indices taking the value 1 or 2, 1 refers to the wall, 2 to human, $j = 1$, if $i = 2$, $j = 2$, if $i = 1$.

The amount of heat, exchanged between the wall and the person is calculated by dependence (2) or (3).

\[
\begin{align*}
Q_{12} &= \varepsilon_n \cdot \sigma_0 \cdot (T_2^4 - T_1^4) \cdot H_{12} \quad (2) \\
Q_{21} &= \varepsilon_n \cdot \sigma_0 \cdot (T_2^4 - T_1^4) \cdot H_{21} \quad (3)
\end{align*}
\]

\[
\varepsilon_n = \frac{1}{1 + \left(\frac{1}{\varepsilon_1} - 1\right) \cdot \varphi_{12} + \left(\frac{1}{\varepsilon_2} - 1\right) \cdot \varphi_{21}} \quad (4)
\]

\[
H_{12} = F_1 \cdot \varphi_{12} \quad (5)
\]

\[
H_{21} = F_2 \cdot \varphi_{21} \quad (6)
\]

where $\varepsilon_n$ is the normalized degree of blackness; $H_{12}$, $H_{21}$ are mutual surface between wall and human or human and wall, respectively, $m^2$; $\varphi_{12}$, $\varphi_{21}$ are irradiance coefficient between the wall and human or human and wall, respectively.

To calculate the irradiance coefficients analytically, it is necessary to calculate the integrals (7), (8) [4-6].

\[
\varphi_{12} = \frac{1}{F_1} \int_{F_1} \int_{F_2} \frac{\cos(\varphi_1) \cdot \cos(\varphi_2)}{\pi \cdot r^2} dF_2 
\]

\[
\varphi_{21} = \frac{1}{F_2} \int_{F_2} \int_{F_1} \frac{\cos(\varphi_1) \cdot \cos(\varphi_2)}{\pi \cdot r^2} dF_2 
\]

where $\varphi_1, \varphi_2$ are angles of radiation incidence on the centers of elementary areas $dF_1, dF_2$; $r$ is the distance between these elementary areas, $m$. 

\[
\varphi_{12} = \frac{1}{F_1} \int_{F_1} \int_{F_2} \frac{\cos(\varphi_1) \cdot \cos(\varphi_2)}{\pi \cdot r^2} dF_2 
\]

\[
\varphi_{21} = \frac{1}{F_2} \int_{F_2} \int_{F_1} \frac{\cos(\varphi_1) \cdot \cos(\varphi_2)}{\pi \cdot r^2} dF_2 
\]
The calculation of these integrals is rather complicated, therefore, for most special cases, the value of this integral can be found in the literature [10-13]. The dependence of the irradiance coefficient between a human and the wall on the geometric parameters is taken from [10]. The irradiance coefficient $\varphi_{21}$ for the calculation cases 1 and 2 is calculated based on this dependence. Next, the mutual surface between a human and the wall is determined according to dependence (6), then according to dependence (3) the heat is found, which the wall and human exchange. From the equality of expressions (5) and (6), which follows from the compatibility property [11], it is possible to calculate the coefficient $\varphi_{12}$, which is necessary to determine the radiation components from the dependences of the system of equations (1). The irradiance coefficient $\varphi_{21}$ for case 3 is calculated by dependence (9).

$$\varphi_{21} = 2 \cdot \varphi_{21,1} + 4 \cdot \varphi_{21,2}$$

where $\varphi_{21,1}$ is the coefficient calculated for case 1, $\varphi_{21,2}$ is the coefficient calculated for case 2.

2.3. Numerical calculations
The ANSYS Steady-State Thermal package was used for numerical simulation. The geometric models for all cases are presented in Figure 1 (a, b, c).

![Figure 1](image_url)

Figure 1. Geometric models for different cases considered:
(a) Case 1, (b) Case 2, (c) Case 3.

Boundary conditions, used in the model are as follows. For the outer surface of the cryosauna wall and the body, boundary conditions of the first type (temperature setting) are used. For the inner surface of the cryosauna wall and the side surface of a human, radiative heat transfer is set. The emissivity coefficient for a human and a wall is taken equal to 0.9.

3. Results and discussion
Figure 2 (a, b) shows the change of radiative heat transfer between the wall and a human, calculated analytically and using Ansys. The root-mean-square error (RMSE) between analytical calculation and Ansys-based calculation was 3.97 W for case 1, 3.7 W – for case 2, and 31.5 W – for case 3. Figure 2 shows that the radiation heat flux between the walls of the cryosauna and a human can be up to 600 W, which is up to 30% of the total heat flux between a human and the air in the cryosauna. It follows the need to take into account radiation heat transfer in the task of calculating heat transfer between a human and a cryosauna. In the future in the problem of radiation-convective heat transfer
for accounting radiation in Ansys, it is possible, both using the automatic switching on radiation (for example by the Monte Carlo method) and using the proposed method to set manually the expression of the radiative heat flux, which will reduce the calculation time.

Figure 2. Radiative heat flux between a human and a wall in different cases: (a) Cases 1, 2, (b) Case 2.

4. Conclusions
One of the main goals of the works devoted to the modeling of cryoinfluence is the planning of the exposure time. In the case of a cryosauna, the exact time will significantly depend on the patient and the initial conditions of the cryosauna. The excessive duration of the procedure will lead to an overconsumption of liquid nitrogen, and in some cases may lead to frostbite of the human skin surface. On the other hand, the too-short procedure will not lead to the desired effect. In this work, the substantiation of the need for more careful consideration of the heat transfer radiant component of the cryosauna-human system is presented, which is neglected by many researchers in this area, or taken into account too simplistically. For example, a cold cryosauna in the first minute of the procedure will have a much greater effect on the patient than a warm one. First of all, this difference will be achieved because in the first case, radiant heat exchange takes place, while in the second case, the system of a human-cryosauna is in radiation heat equilibrium. Another area in which the proposed approach can provide new information for analysis is the choice of materials for the inner wall of the cryosauna. Thus, even though the results shown in this article apply only to a limited area of cryoinfluence, this article has proved the need for careful consideration of radiant heat transfer in all cases of cryotherapy.

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