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CFD SIMULATION OF THERMO- AERODYNAMIC INTERACTION IN A SYSTEM HUMAN- CLOTH- ENVIRONMENT UNDER VERY LOW TEMPERATURE AND WIND CONDITIONS

Irina Cherunova[1], **Sina Samarbakhsh**[2] **and Nikolai Kornev**[2]

[1]Don State Technical University
Shevchenko str. 147, 346500 Shakhty, Russia
e-mail: i_sch@mail.ru

[2] University of Rostock
A. Einstein Str.2, 18059 Rostock, Germany
e-mail: nikolai.kornev@uni-rostock.de

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Abstract. *The paper presents study of coupled aerodynamic and thermodynamic interaction between human body and environment under low temperature and wind conditions. The passive heating or the prescribed heat flux model is used to model the metabolic heat release by human body. The heat flux is selected from the condition that the surface temperatures take experimental values for certain environmental conditions. Heat transport inside of the clothes, radiation, natural and forced convection are simulated using OpenFOAM toolkit. Results are obtained for the schematic human body in form of a cylinder and real body. It was shown that only forced convection and heat conduction play an essential role at wind conditions and low temperatures whereas the radiation and natural convection can be neglected. To keep the human body temperature on the acceptable level, the local heating elements can be embedded into the clothes textile. The power of this heating was calculated using the models of aero-thermodynamic coupled interaction including heat radiation. Under strong wind conditions the heat transfer from the human body can sufficiently be increased due to change of the thermal conductivity caused by cloth deformation under wind induced pressures. The results of the work are used for the design of real protection clothes for the work under low temperatures and wind conditions in oil gas industry.*

1 INTRODUCTION

Modeling the interaction in the system human- clothes - environment is a very complex interdisciplinary research subject requiring different competencies in the fields of physiology, thermodynamics, fluid mechanics and textile sciences. The simulation in the field of human thermodynamics can be done using either physical human body models (thermal manikins), which are manufactured in full size, or mathematical models. The manikins are equipped with heat wires and temperature sensors to imitate heat transfer over the entire body . Among the limitations of the experimental studies with manikins one can mention high costs in manufacturing. Technically, it's very difficult to divide a manikin in many partitions with different heating power and study the temperature distribution over the entire body surface. Moreover, it is impossible to separate the effects of convection and radiation, since various sensors are required for these phenomena. Even if all these difficulties can be overcome, the manikin remains a model and relies on many assumptions.

With a rapid development of numerical methods the focus of the investigation of the interaction between human and the environment is increasingly being shifted in the direction of the computer simulations. Development of the theoretical basis for modeling interactions in the human-clothing-environment and the design of intelligent smart clothing requires the development of the following three sub-models:

• mathematical model for the human thermodynamics with consideration of thermal conduction, heat transport by the blood, radiation, respiration, heat release by internal organs and active response of the body.

• mathematical model for heat transport in clothes and in the under garment space with taking into account humidity, permeability of clothing, anisotropy of heat propagation within the cloth, non-uniformity of the air layers between the body and clothes as well as between different layers of cloth. For the intelligent or smart clothes the internal heating inside the clothes should be modeled.

• mathematical model for the transport of the heat from the human body to the environment through the radiation, thermal conduction, natural and forced convections.

Short description of the mathematical model used in this paper is presented in the next section.

2 MATHEMATICAL MODEL

The first models for internal human thermodynamics were proposed by Fanger [1] and Stolwijk [2]. One of the most successful and widely used models of human thermoregulation, which also represents the state of the art in this field, has been developed by Fiala [3]. The group of models proposed by Stolwijk [2] and Fiala [3] are based on the partial differential equations describing the heat transport in cross sections of body which are coupled through the blood transport along the body. Since such models are not quite reliable we use a simplified model specifying the heat flux on the body surface $\dot{q}$ (prescribed wall heat flux). In this case, the body heat production is taken into account by a heat flux $\dot{q}$ distributed over the body either homogeneously as $\dot{q} = Q_{total}/A$, where Q_{total} is the total heat released by the body and A is the surface of the human body, or non homogeneously with use of empirical data on skin temperature.

The heat transport within the clothes occurs mainly due to the thermal diffusion, although the effects of natural and forced convection caused by the movement of people (bellows effect) are also available. Strictly speaking, the heat propagation in clothes is anisotropic because of the specific textile structure. The application of simple temperature equations with an isotropic

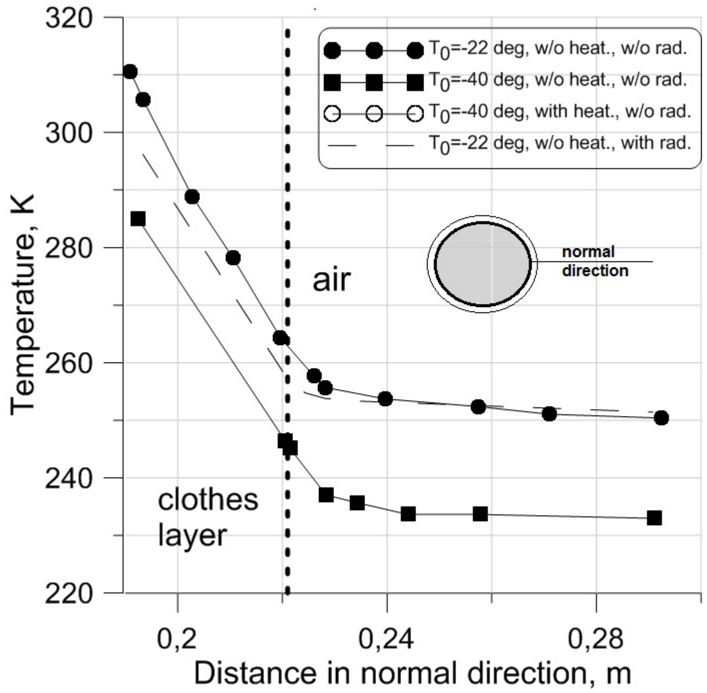

Figure 1: Distribution of the temperature in the normal direction to cylinder with clothes layer. Cases 1-1, 1-2, 2-1, 2-4.

scalar heat conduction coefficient is not correct. However, since the clothes is relatively thin, one can neglect the anisotropy and determine an integral value for the coefficient of the conduction from the measurements. In the present paper, the clothes is considered to be a solid body with the thermodynamic properties determined from experiments. The folding of the cloth, the bellows effect and irregularity of the air insulation layer are not considered.

Forced convection is calculated using the incompressible flow model with the temperature considered as a passive scalar determined from the temperature transport equation. The turbulent flow was calculated using steady RANS (Reynolds Averaged Navier- Stokes Equations) with the $k-\varepsilon$ (sec. 3.1) and $k-\omega$ SST models (sec. 3.2).

The framework OpenFOAM [4] was utilized for the numerical solution of the total problem. Four different models are available in OpenFOAM for calculating the radiation : fvDOM, P1, opaque solid and view factor models.

3 RESULTS

Before performing calculations for the real human body we studied a more simple case in which the body is schematically represented by a cylinder. This is done to avoid serious problems arising due to irregularity of the real human body surface and complex grids. Using a simplified body model we determined the heat transport phenomena which can be neglected when considering the real body model.

3.1 Preliminary study using cylinder model with cloth

The study was performed for a cylinder with the height of 1500 mm and a diameter of 382 mm, which mimics the human body approximately. The surface of the cylinder is $1.9m^2$ which corresponds to the human body surface. The cylinder case seems to be relevant since the heat conduction takes place mainly in the normal direction similar to the body case. The study was performed at low and very low temperatures with consideration of the radiation, natural and forced convections. To model the protecting influence of cloth, an outer layer with the thickness of 30 mm was inserted as a cover of the cylinder. The coefficient of thermal conductivity of the layer is equal to this of the real clothes (s. subsec. 3.2.2).

Table 1: **Summary of cases**

Case	Air temperature ^0C	Wind speed m/s	Radiation	Metabolic heat release W	Internal heating W	Body surface temperature ^0C	clothes surface temperature ^0C
1-1	-22	0	No	85	0	30.5	-8.3
1-2	-22	0	Yes	85	0	23.9	-15.3
2-1	-40	0	No	85	0	12.0	-27.0
2-2	-40	0	No	85	55	29.5	-21.0
3-1	-40	5	No	85	0	3.2	NA
3-2	-40	5	No	85	105	29.5	-31.0
3-3	-40	5	Yes	85	105	28.2	-31.8
3-4	-40	10	No	85	118.4	29.0	-33.2

The calculation cases are summarized in table 1. Two different ambient air temperatures were examined: -22^0C and -40^0C. The boundary layer created by the natural convection can be either laminar or turbulent depending on the ratio between the buoyancy and the viscous forces, which is characterized by the Rayleigh number $Ra = GrPr$, where Gr and Pr are the Grashof and Prandtl numbers respectively. Since for the cases under consideration the Rayleigh number is 2.31×10^9 the flow caused by natural convection is turbulent. The standard $k - \varepsilon$ is applied. The degree of turbulence at the inlet amounts to 10% what at the speed of $u = 0.5m/s$ corresponds to the r.m.s of $u^/ = 0.05m/s$, while the turbulent kinetic energy is $k = 3/2u^{/2} = 0.00375m^2/s^2$. The dissipation rate ε calculated using the integral length of $l = 5cm$ is $\varepsilon = C_\mu k^{3/2}/l = 4.13 \cdot 10^{-4}m^2/s^3$. The prescribed heat flux of 85 Watts distributed uniformly over the cylinder surface simulates the metabolism heat release. This value allows one to obtain the temperature of 30^0C on the body surface. Calculations were performed with the code OpenFoam [4]. To couple the air environment with the solid bodies including the cloth the turbulent TemperatureCoupledBaffleMixed routine is used. A special interface has been introduced in order to thermally couple the air environment and solid body. The available in OpenFoam routine turbulentTemperatureRadCoupledMixed condition was applied to model the radiation.

3.1.1 Effect of natural convection

The natural convection is caused by the density differences that occur in proximity to the body due to the heating of the air. Heat transfer from the body is caused in this case by the two following mechanisms: molecular thermal conduction (thermal diffusivity) and the heat transport by the air movement. Four calculation cases 1-1, 1-2, 2-1 an 2-2 were investigated with account for the natural convection. The temperature distribution along the line, which is perpendicular to the cylinder surface, is shown in Fig. 1. The abscissa $0.191m$ corresponds to the body surface, while $0.221m$ represents the outer boundary of the clothes. Through the metabolic heat release of $85W$ the body temperature (Case 1-1) reaches the value of 30.5^0C when the air temperature is -22^0C. This result is consistent with the experimental observations performed by the first author (IC) in the climate chamber with real test person. The insulating protective clothes allows to hold the body temperature at a comfortable level of 30^0C without additional heating. The temperature of the upper boundary of the clothes is negative and amounts to -8.31^0C (see case 1-1 in the table 1). If the ambient air temperature decreases to -40^0C, the body temperature reduces to 12^0C, while the temperature of the outer clothes boundary sinks to -27^0C (s. case 2-1). Although a simplified geometry is considered, the results are more plausible and physically than our previous results for the realistic human body [5]. The temperature at the upper limit of the clothes is negative. This was achieved by reducing the numerical error caused by irregular body surface and grid problems. To attain a comfortable temperature at $T_0 = -40^0C$ we use the smart clothes with the internal heating placed at the interface surface between the body and the cloth. From calculations it was found that the heating power of $55W$ is required to bring the body temperature at 29.50^0C (s . Fig. 1 and case 2-2 in Table 1). The temperature of the clothes boundary is -21^0C for this case.

3.1.2 Effect of radiation

In this paper the opaque solid model was used which takes the radiation within the clothes into account. The emissivity was set equal to the value of 0.9. The results are presented in Fig. 1 and case 1-2 in table 1. As can be seen , the body temperature drops by radiation from 30.5^0C to 23.9^0C. Therefore the comfort conditions documented in the case 1-1 are disturbed by the radiation .

3.1.3 Effect of forced convection

Forced convection has a crucial effect on the heat interaction between human body and environment especially at low temperatures. In this work, four cases listed in the table 1 as cases 3 are studied. The ambient temperature was in all cases -40^0C. The results show that the forced convection caused by the wind of $5m/s$ results in the drop of the body temperature to 3^0C without heating (s. case 3-1). In order to achieve the comfortable body temperature of around 30^0C, the internal heating of $105W$ is required (see case 3-2 in table 1). It is noteworthy that the radiation at the wind conditions is completely meaningless (s. Fig. 2 and compare cases 3-2 and 3-3). When the wind has the speed of $10m/s$ the required internal heating should have the power of $118.4W$ (see case 3-4). Concluding, when the heat exchange between the human body and environment is calculated at low temperatures only forced convection and thermal diffusion can be taken into account. Other effects like the radiation and natural convection are negligible.

3.2 Results for the human body model with cloth.

3.2.1 Human body model, computational domain and grid.

The finite volume method is implemented on an unstructured grid with approximately $4.3M$ of cells in the computational domain $15m \times 5.5m \times 5.5m$. Elongation of the computational domain in the longitudinal direction is necessary to calculate the wake effect. The grid has different resolutions in different areas. The finest unstructured grid is located in the block of $3m \times 1.8m \times 1.8m$ closest to the body. Away from the body the grid resolution is gradually reduced having relatively high resolution in the block $7.5m \times 3.6m \times 3.6m$. The real human body geometry of height of $1.8m$ designed at the Hohenstein Institute on the basis of the detailed

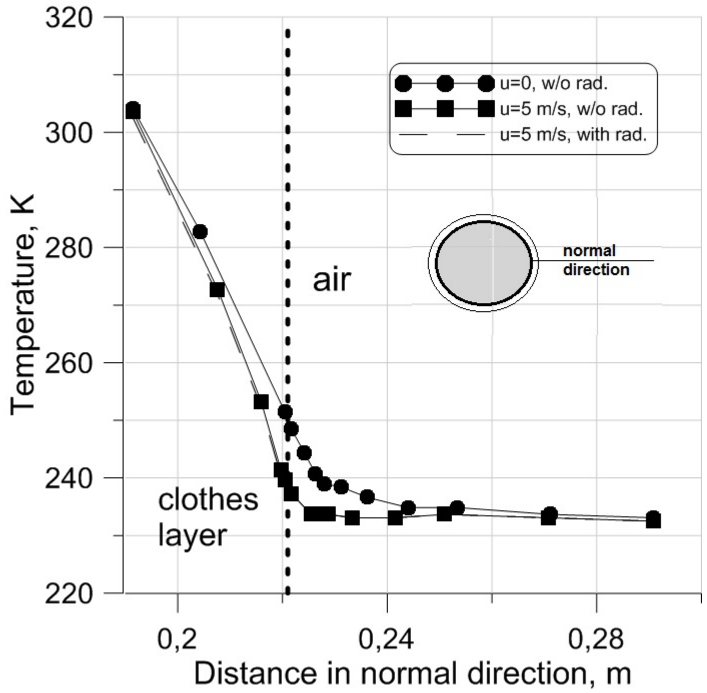

Figure 2: Distribution of the temperature in the normal direction to cylinder with clothes layer. Cases 2-2, 3-2, 3-3.

anthropological study of different categories of peoples is located in the symmetry plane at 5m from the inlet of the computational domain. For reliable resolution of the temperature boundary layers six thin prism layers are added on the inner and the outer surfaces of the cloth. A thin prism layer of the thickness of $1mm$ adjacent to the inner air layer between the clothes and the body is served as the heating layer with heat release source f.

3.2.2 Clothes construction

A clothes of thickness 30 mm comprises a savior, a flamestat cotton (upper sheet), an insulation thinsulate, and a taffeta as a lining. This clothes is used in oil industry for work at very low temperatures under oil contamination conditions. The air layer of the thickness of $10mm$ is located between the clothes and the body. The clothes textile has the following properties: the heat capacity is $C_p = 1800J/kgK$, the density is $8.57kg/m^3$, the thermal conductivity is $\lambda = 0.04W/mK$.

3.2.3 Prescribed heat flux model of the human body

The heat flux $\dot{q}$ is calculated from the condition that the resulting temperatures from simulations are equal to these measured on the real human body clothed in the protection coverall. Temperature measurements were performed at -22 deg of the ambient air at 18 points directly on the skin of the human body. The body surface is subdivided into 34 elements. The heat flux on each element was varied as long as the temperature on the skin from simulations is approximately equal to the measured ones. Details of this procedure are presented in [5].

3.2.4 Results for internal heating

The aim of the calculation is the determination of the heat release f which allows one to maintain the temperature on the body skin in the comfortable range at the temperature of the ambient air of -40° without wind. The comfortable body skin temperatures are taken from the measurements performed at -22° with the real human clothed in the protection coverall. In numerical simulations the area and the power were varied as long as the simulated temperature at 18 points is close to the comfortable one. The heating elements were selected under the following conditions:

• Heating elements can not be located close to the sensible inner organs because it can have negative impact on health,
• Heating elements can not be located in zones of high sweating,
• The necessary area of the heating elements and heating power should be minimal,
• Both overheating and under heating of the body should be avoided.

Distribution of heating elements with necessary area and heat flux as well as the temperature distributions on the body skin are given in Fig. 3. The total heat flux necessary to maintain the comfortable temperatures is estimated as 60 Watt. This result obtained for the real human body is very close to this for the cylinder. Therefore, we can expect the same result for the case with wind speed. i.e. the power necessary to attain the comfortable temperature on the real body for the wind speed of $5m/s$ is around $105W$.

3.2.5 Clothes deformation due to wind induced pressure.

Wind causes big areas of the overpressure on the clothes surface which results in deformations and local change of the clothes thickness. In its turn, change of the local thickness leads to an alteration of heat conduction properties of the cloth. This means that the heat exchange between body and air is changed not only by intensification of convective heat transfer but also due to change of thermodynamic properties of clothes caused by wind induced deformations. The second effect has still not been discussed thoroughly in the literature. Under strong wind conditions the heat transfer from the human body can sufficiently be increased due to change of the thermal conductivity caused by cloth deformation under wind induced pressures. For instance, at 10 m/s the heat increase could be of ten percent. For the details of this study the reader is referred to the work [6].

4 CONCLUSIONS

The paper presents an application of numerical simulations for design of a special clothes for work under extremely low temperatures. The heating elements inside of the clothes are applied to maintain the comfortable temperatures on the body skin. The distribution of the temperature on the body, in the cloth, in the air layer between the body and the clothes and in the ambient air is calculated from the transport equations using the OpenFoam toolkit. Results are obtained for the schematic human body in form of a cylinder and real body. It was shown that only forced convection and heat conduction play an essential role at wind conditions and low temperatures whereas the radiation and natural convection can be neglected. Sizes and the power of heating elements are selected from numerical simulations. At present present numerical results are used to construct the protecting coverall of the new generation for employees of the gas and oil industry.

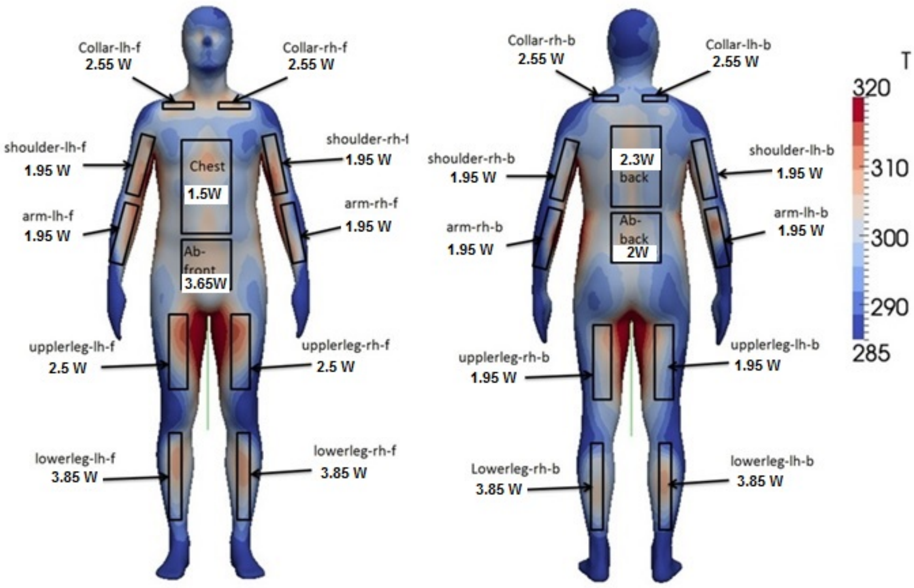

Figure 3: Power of the heating elements and the temperature distribution at the human body at -40^0C of the surrounding air. CFD calculations with OpenFoam program.

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