VI International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2015
B. Schrefler, E. Oñate and M. Papadrakakis(Eds)

COUPLED THERMO- AERODYNAMICAL PROBLEMS IN DESIGN OF PROTECTION CLOTH

IRINA CHERUNOVA*, **MAHESH DHONE**† **AND NIKOLAI KORNEV**†

*Don State Technical University
Shevchenko str. 147, 346500 Shakhty, Russia
e-mail: i_sch@mail.ru, web page: http://www.sssu.ru/

†University of Rostock
A. Einstein Str.2, 18059 Rostock, Germany
e-mail: nikolai.kornev@uni-rostock.de - Web page: http://www.uni-rostock.de/

Key words: Human Thermodynamics, Conjugate Heat Transfer, Computational Fluid Dynamics, Cloth Design

Abstract. The paper presents results of calculation of thermodynamic interaction between the human body and the ambient air at very low temperatures. The numan body is clothed in a warm coverall. Temperature transport is calculated numerically by the solution of heat conduction equation. Simplified thermodynamic model of the human body by the surface heat flux obtained from empirical data is applied. Results of investigations are used for design of real protection cloth.

1 INTRODUCTION

Aerodynamic and thermodynamic interaction between body and environment under low temperature and wind conditions is a typical problem with thermomechanical coupling of fluids (air or water) and structures (human body and clothes). The body generates the heat within certain organs which is then transferred by the thermal diffusion through the body substance possessing very non uniform properties. A large fraction of the heat generated by internal organs is transported to the body periphery by a complicated net of blood vessels. The heat penetrates through the cloth and is transferred to surrounding medium by natural and forced convections. Wind causes big areas of the overpressure on the cloth surface which results in deformations and local change of the cloth 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 cloth caused by wind induced deformations.

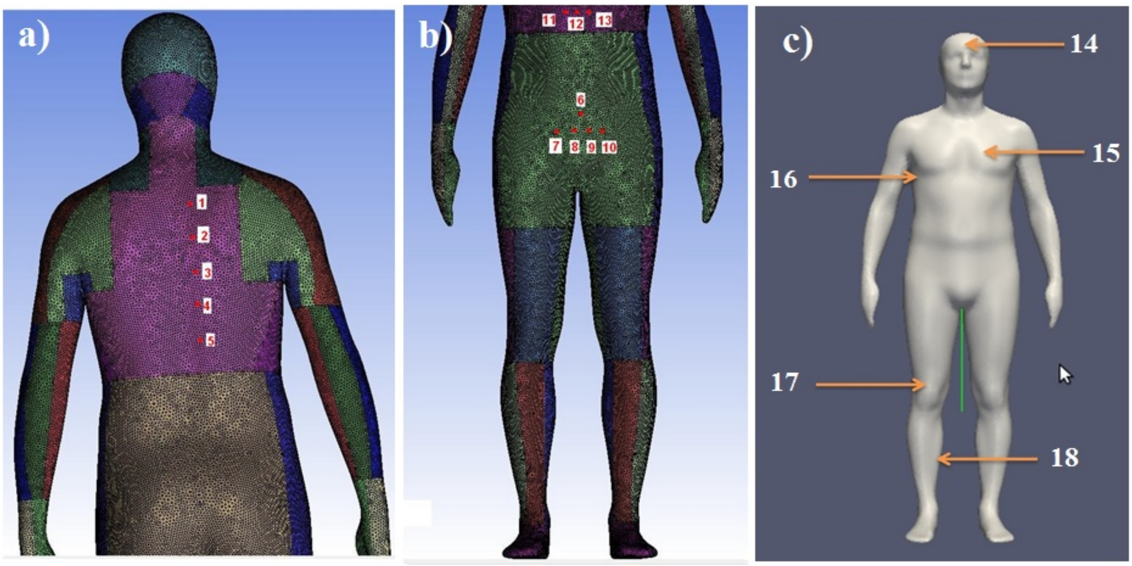

Figure 1: Points on the skin where the temperature is measured and calculated

The second effect which has still not been discussed thoroughly in the literature has been considered in our previous papers [1], [2] and [3]. 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 [2].

In this paper we restricted ourselves to the problem of interaction of body with surrounding medium through the heat diffusion and radiation. Since the wind influence has already been considered in our paper [2] it is not discussed here. Results of the present analysis are used for design of protection cloth with heating. To keep the human body temperature on the acceptable level, the local heating elements are embedded into the cloth textile. The power of this heating is calculated numerically. The results of the paper are utilized for the design of real protection cloth for the work under low temperatures and wind conditions in oil and gas industry.

2 MATHEMATICAL MODEL

2.1 Governing equation

The heat transport in the system "human body-cloth-ambient air" is described by the unsteady heat conduction equation

$$\rho C_p \frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + f \qquad (1)$$

where the specific heat capacity C_p, the heat conduction coefficient λ and the density ρ are changed depending on the material where the heat is conducted. f is the heat release source. The steady state solution is obtained from time marching unsteady simulation. The equation (1) is solved with the Neumann boundary condition

$$\dot{q} = \dot{q}_{specified}, \text{ on the human body} \tag{2}$$

enforced on the body surface and the Dirichlet boundary condition

$$T = T_{air}, \text{ away from the human body} \tag{3}$$

enforced at the outer boundary of the computational domain.

2.2 Numerical implementation

The equation (1) is solved numerically using the OpenFoam toolkit [4]. The finite volume method is implemented on an unstructured grid with approximately 4.3 Mio of cells in the computational domain $15m \times 5.5m \times 5.5m$. Elongation of the computational domain in the longitudinal direction is because the same grid is applied for thermo-aerodynamic calculations which will be presented later. 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 [5] on the basis of the detailed 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 cloth and the body is served as the heating layer with heat release source f.

2.3 Cloth construction

A cloth of thickness 30 mm comprises a savior, a flamestat cotton (upper sheet), an insulation thinsulate, and a taffeta as a lining. This cloth 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 cloth and the body. The cloth textile has the following properties: the heat capacity is $C_p = 1800J/kgK$, the density is $8.57kg/m^3$, the thermal conductivity is $\lambda = 0.04W/mK$.

2.4 Simplified thermodynamic model of the human body by the surface heat flux obtained from empirical data

The heat release from the human body can be calculated using relatively simple models based on empirical information. The group of models proposed by Stolwijk and Fiala [6], [7] 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 $\dot{q}$. 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 shown in Fig. 1 directly on the skin of the human body. Results of calculations performed without wind speed are presented in the table 1. The body surface is subdivided into 34 elements (see Fig. 2). The heat flux on each element was varied as long as the temperature on the skin from simulations (second column in table 1) is approximately equal to the measured ones (first column in table 1). As follows from the fourth column in the table 1 the heat flux given in Fig. 2 provides the temperature distribution close to the measured one with the discrepancy less than five percent with the only exception at point 5. The total heat flux necessary to maintain prescribed temperatures is around $31W$. This flux doesn't take the radiation and sweating into account. Consideration of these additional effects results in the total heat flux about 70 Watt.

The data presented in Fig. 2 is some kind of thermodynamic model of the human body. To prove it we used an additional test. At the temperature of $+29°$ of Celsius of ambient air the human body is in equilibrium with air and has the temperature of the skin around +29 deg. To escape generation of new grids we use the copper cloth instead of textile one. The copper possesses very high conductivity $\lambda = 401W/mK$ and acts as an ideal conductors of the heat from body as though there is no cloth. The temperature distribution obtained for this case is presented in the fifth column of the table 1 which is close to the equilibrium temperature $29°$. The discrepancy is around five percent. Therefore the simplified model thermodynamic model of the human body by the surface heat flux obtained from empirical data can be considered as the reliable one.

3 RESULTS

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 $-40°$. The comfortable body skin temperatures are taken from the measurements performed at $-22°$ with the real human clothed in the protection coverall (see column 2 in the table 1). In numerical simulations the area and the power were varied as long as the simulated temperature at 18 points shown in Fig.1 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 is given in Fig. 3. The total heat flux necessary to maintain the comfortable temperatures is estimated

Table 1: Temperature distribution at 18 points at −22 deg with cloth, without heating: measurement (second column), simulation (third column) and difference between measurement and simulation (fourth column) and at +29 deg without cloth: simulation (fifth column) and difference between measurement and simulation (last column).

Point	Experiment deg	Simulation deg	Error %	Simulation deg	Error %
Air temperature		−22 deg		+29 deg	
1	31.50	30.72	2.5	30.73	5.5
2	32.80	32.01	2.4	30.74	5.3
3	32.40	32.55	0.5	30.77	5.5
4	33.90	34.21	0 .9	30.82	5.4
5	32.20	34.41	6.9	30.88	5.8
6	31.40	32.05	2.1	30.71	5.4
7	32.80	33.06	0.8	30.73	5.3
8	32.40	32.38	0.1	30.72	5.3
9	33.80	32.32	4.4	30.72	5.1
10	32.10	32.71	1.9	30.72	5.4
11	32.90	32.70	0.6	30.71	5.2
12	32.60	33.43	2.5	30.71	5.2
13	34.00	32.90	3.2	30.71	5.0
14	29.67	29.37	1.0	29.28	0.9
15	31.20	31.23	0.1	29.75	2.4
16	34.82	34.85	0.1	30.20	3.4
17	23.49	23.52	0.1	29.73	3.1
18	26.75	26.63	0.4	29.65	2.4

as 12 Watt. Additionally about 30 Watt of the heat flux are necessary to cover the heat loss due to radiation. The final temperature distribution presented in the table 2 gives the averaged discrepancy of 0.44° and the biggest local discrepancy of 1.06° at the point 9. Figure 4 shows temperature distributions on the body skin at the ambient air temperatures of −22° and −40°. Obviously, the numerical simulations have a serious disadvantage in areas of contacts of different body parts, i.e. legs and hands. These artifacts of a pure numerical nature can be eliminated by increase of resolution in contact areas. Within this paper these regions are simply excluded from analysis.

4 CONCLUSIONS

The paper presents an application of numerical simulations for design of a special cloth for work under extremely low temperatures. The heating elements inside of the cloth are

Table 2: Temperature distribution at 18 points at -40 deg with cloth and heating: comfort temperature (second column), simulation (third column) and difference between the comfort temperature and simulation (fourth column).

Point	Comfortable T	Simulation	Error
1	31.5	30.72	0.78
2	32.8	33.70	0.90
3	32.4	33.01	0.61
4	33.9	33.27	0.63
5	32.2	31.65	0.55
6	31.4	31.34	0.06
7	32.8	32.67	0.13
8	32.4	32.25	0.15
9	33.8	32.74	1.06
10	32.1	31.98	0.12
11	32.9	33.11	0.21
12	32.6	32.54	0.06
13	34.0	34.46	0.46
15	31.20	30.54	0.66
16	34.82	34.55	0.27
17	23.49	23.27	0.22
18	26.75	26.20	0.55

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 cloth and in the ambient air is calculated from the temperature transport equation using the OpenFoam toolkit. Sizes and the power of heating elements are selected from numerical simulations. The results of numerical simulations seem to be reliable with exception in areas of contacts of different body parts. Results with account of full thermo- aerodynamic interaction will be presented in next works of the authors. At present the numerical results are used to construct the protecting coverall of the new generation for employees of the gas and oil industry.

Acknowledgments. This work was carried out with the financial support within the framework of the joint project 11032p/20253 of the German Federal Ministry of Education and Research (BMBF) and the Russian Foundation for Assistance to Small Innovative Enterprises (FASIE).

REFERENCES

[1] Cherunova I., Jacobi G. and Kornev N. Study of human body aerodynamics for protection cloth design. *Proceedings of the 6th International Conference on Vortex Flows and Vortex Models*, November 17-20, 2014, Nagoya, Japan.

[2] Cherunova I., Kornev N., Jacobi G., Treshchun I., Gross A., Turnow J., Schreier S. and Paschen M. Application of computational heat transfer and fluid mechanics for protection cloth design. *Journal of Engineering Physics and Thermophysics* (2014), **87(4)**:829–837. Vol. 87, No. 4, pp. 829-837.

[3] Cherunova I., Kornev N., Jacobi G., Treshchun I., Gross A., Turnow J., Schreier S. and Paschen M. Application of computational fluid mechanics for protection cloth design. *Proceedings of the 11th World Congress on Computational Mechanics (WCCM XI)*, 22.-25.07.2014, Barcelona, Spain.

[4] Weller, H.G., Tabor, G., Jasak, H. and Fureby C. A tensorial approach to CFD using object oriented techniques, *Computers in Physics* (1998), **12(6)**: 620–631.

[5] www.hohenstein.de

[6] Fiala, D., Lomas K.J., Stohrer M.. Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. *Int. J. Biometeorol* (2001), **45**:143159.

[7] Cherunova, N. Kornev, and I. Brink. Mathematical model of the ice protection of a human body at high temperatures of surrounding medium, *Eng. Research* (2012), **76(3)**:97–103.

Body part	Area	Heat flux	Total heat flux
abdomen front	0.163	16.92	2.76
abdomen inferior	0.1175	15.83	1.86
abdomen posterior	0.161	15.83	2.55
face front	0.0132	26.57	0.35
face superior	0.0152	26.57	0.4
feet front	0.11	15.83	1.74
feet posterior	0.0358	15.83	0.57
hand inferior	0.0452	15.83	0.72
hand superior	0.0438	15.83	0.69
head-front	0.0061	26.57	0.16
head-posterior	0.0626	26.57	1.66
lower-arms-front	0.163	15.83	2.58
lower-arms-inferior	0.163	15.83	2.58
lower-arms-posterior	0.163	15.83	2.58
lower-arms superior	0.163	15.83	2.58
lower legs-front	0.185	17.37	3.21
lower legs inferior	0.185	17.37	3.21
lower legs posterior	0.185	17.37	3.21
lower legs superior	0.185	17.37	3.21
neck front	0.0303	15.83	0.48
neck posterior	0.0303	15.83	0.48
neck superior	0.0303	15.83	0.48
shoulder	0.0337	15.83	0.53
thorax front	0.115	18.1	2.08
thorax inferior	0.032	2.54	0.08
thorax posterior	0.104	15.83	1.65
upper arms front	0.149	15.83	2.36
upper arms posterior	0.149	15.83	2.36
upper arms superior	0.149	15.83	2.36
upper arms inferior	0.025	2.54	0.06
upper legs front	0.26	15.31	3.98
upper legs-inferior	0.26	15.31	3.98
upper legs-posterior	0.26	15.31	3.98
upper legs superior	0.26	15.31	3.98

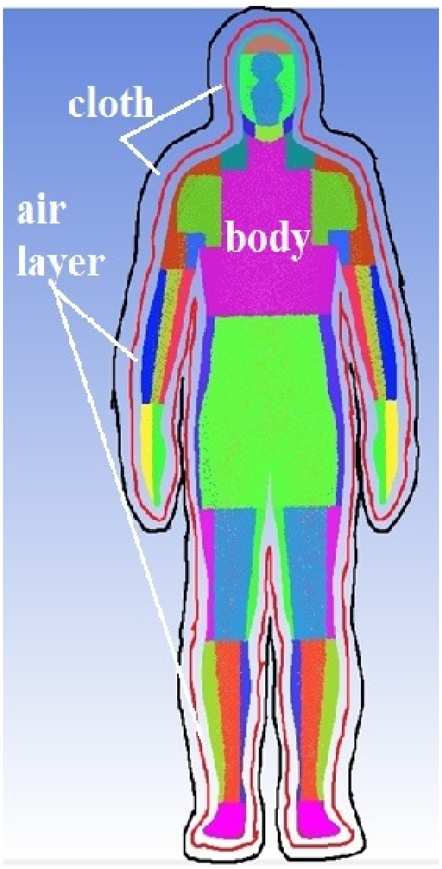

Figure 2: Distribution of the heat flux in W/m^2 (third column) and the total heat flux in Watt on different body parts which is necessary to get the temperature distribution obtained from measurement (see 2nd column in the table 1).

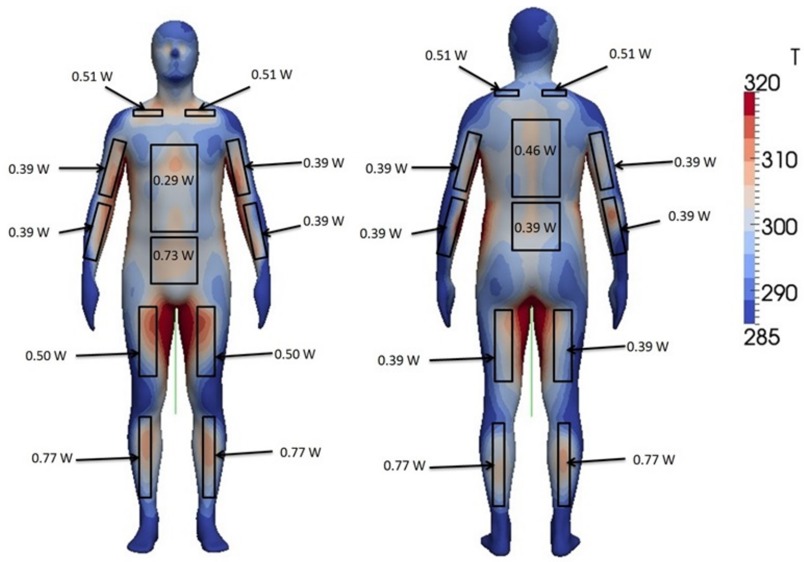

Figure 3: Distribution of heating elements and their power necessary to maintain the comfortable temperature at the temperature of the ambient air of $-40°$.

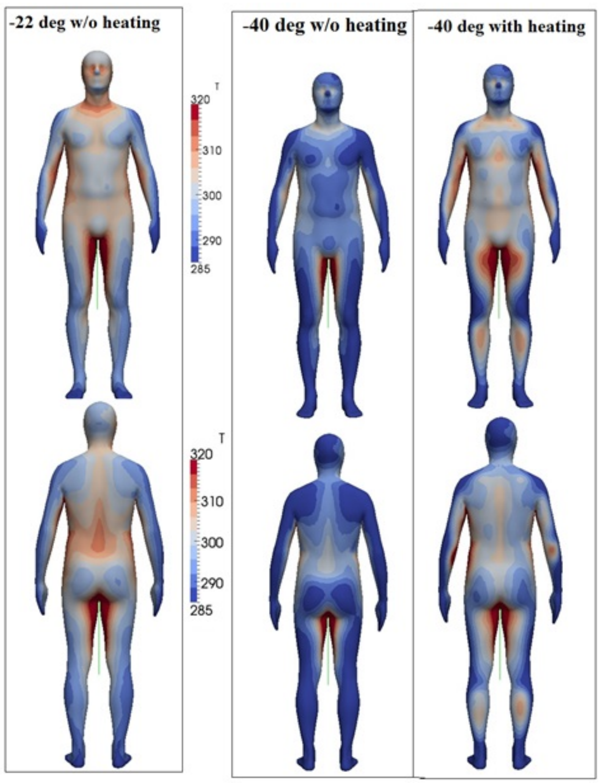

Figure 4: Temperature distribution on the body in cloth: left: $-22°$ without heating, middle: $-40°$ without heating, right: $-40°$ with heating.