8218

BUILDING RESEARCH AND INFORMATION VOLUME 22 NUMBER 6 1994

CFD simulation on the air flow in a sauna

FRESH AIR INLET POSITION INFLUENCES AIR FLOW AND TEMPERATURE DISTRIBUTION WHILST RADIANT HEAT EMISSION TAKES ABOUT 75% OF TOTAL STOVE HEAT OUTPUT

Y. Fan, R. Holmberg and J. Heikkinen

VTT Building Technology, Indoor Environment and Systems, Box 1804, 02044 VTT, Finland

Sauna is the Finnish word for a wood-lined and insulated room, heated by a special stove containing stones, and erected specifically to create the right environment for a certain kind of dry bath. Its fundamental purpose is to induce perspiration and thus to cleanse the skin and body. The authors have now applied scientific data to the mystique and culture of the often misunderstood Sauna which has been used by the Finns for some two thousand years.

Le mot "sauna", d'origine finnoise, désigne la cabine habillée de bois et isolée que l'on chauffe à l'aide d'un poêle spécial contenant des pierres. Spécifiquement conçu pour créer l'environnement approprié à un certain type de bain sec, le sauna génère une chaleur qui intensifie la transpiration, et purifie ainsi la peau et le corps. Les auteurs offrent des informations scientifiques concernant les processus inhérents à ce type de bain – souvent mal compris – qui fait partie de la culture finlandaise depuis près de deux mille ans.

Keywords: Sauna, Finnish tradition, culture, air flow measurements

Introduction

Sauna is a part of Finnish culture which has brought the Finns and their visitors both excellent feelings and good health. However, the mechanism of the sauna seems to be not totally understood even until now. Recently, Äikäs and Holmberg [1] conducted a laboratory test on a sauna and produced some useful results. It is a fact that within the Finnish sauna the air temperature is typically, in the range of 60–100°C. Thus, general measuring apparatus do not work properly making it difficult to obtain useful results. In order to get a closer look at sauna, it has been decided to use the CFD technique to find out more details concerning air flow within a sauna.

The sauna in consideration is the same as the one which Äikäs and Holmberg had tested. The sauna has a cubic volume with a dimension of 2 x 2 x 2 m. Within the sauna, the stove is positioned in a corner of the space 200 mm above the floor, which can supply heat with about 5.5 kW in steady state conditions. With respect to the fresh air supply, two cases will be considered: one in which the air is delivered into the space from the bottom of the stove 150 mm above the floor; the other one in which the air is delivered into the space from the side wall (1450 mm above the floor) above the stove. The exhaust inlet is positioned at the high level of another side wall opposite the air supply. The sauna is sketched in Fig. 1.

CFD simulations are performed by using the WISH program, which was originally developed by Lemaire [2]. The simulation system is described by a Cartesian grid and the air flow can be either laminar or turbulent. The basic model equations are based on high Reynolds number k-ε approach. A more detailed description of the WISH program may be found in Lemaire [2] (usage), Heikkinen [3] (validation), and Chen [4] (mathematical bases).

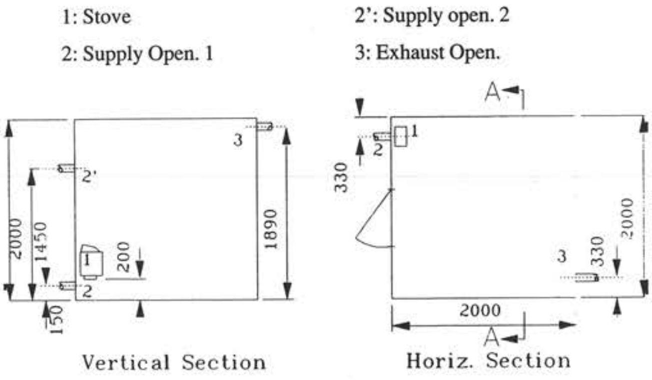


Fig. 1. The sauna under consideration.

0961–3218 © 1994 E. & F. N. Spon

Typically, the space of a sauna is small and the stone surface temperature is in the range of 260–310°C. An understanding of the heat transfer mechanism will be of benefit for the design of the sauna stove and the sauna itself. The question is, does the radiant heat transfer or the convective heat transfer play the main role? The radiant heat transfer between the stove and internal surfaces of the sauna can also be performed by using an analogue thermal network method.

Radiant heat transfer in sauna

The stove used in the sauna under consideration has the dimension of 250 x 512 x 550 (height) mm. To make the simulation easier, the sauna is simplified into four regions based on Äikäs and Holmberg's test (see Fig. 2). In each region, even temperature distribution is assumed, whose value is shown in Table 1, as follows. Other assumptions are: no radiant heat emission from the side and bottom surfaces of the stove, and each surface within the sauna is radiant heat transfer grey with the emissivity of 0.9.

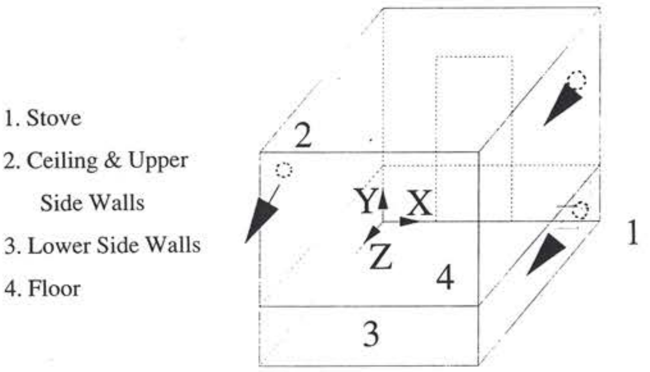


Fig. 2. Simplified sauna model.

Table 1. Temperature for each region in the simplified sauna model

Region	1	2	3	4
Temperature (°C)	270.0	80.0	57.5	35.0

The radiant heat transfer between the surfaces in sauna can be handled by considering the following issues: the radiant heat transfer can occur only when the thermal wave can overcome the 'resistances' arising from the fact that the surface is not black (the surface resistance) and that one surface may not be directly opposite another surface (the space resistance). Then an analogue thermal network can be generated. For this case, it is shown in Fig.3. In this figure, the surface resistance and space resistance as well as other parameters are defined as follows:

$$Rs = \frac{1-\varepsilon}{\varepsilon Fs}; \quad Rp = \frac{1}{\varphi Fs}$$
$$Eb = 5.67\left(\frac{T}{100}\right)^4 \qquad (1)$$

where: Rs = Surface resistance, Rp = space resistance, Eb = radiant heat emission power, Wm^{-2}, T = Absolute temperature of the surface in consideration, K, Fs = Surface area, m^2, ε = emissivity, φ = view factor.

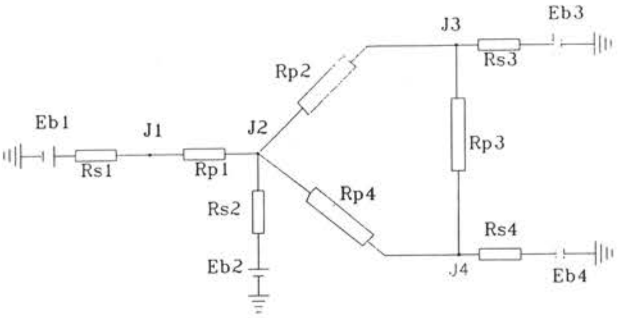


Fig. 3. Thermal network.

For each node, the heat flux will obey the Kirchhoff law. Thus the thermal potential in each node will be governed by the following equations:

$$-7.782J_1 + 6.782J_2 = -4929.27 \qquad (2)$$

$$7.8125J_1 - 134.2775J_2 + 0.089J_3 + 0.376J_4 = -110\,930.4 \qquad (3)$$

$$0.089J_2 - 54.579J_3 + .49J_4 = -36\,531.0 \qquad (4)$$

$$0.376J_2 + 0.49J_3 - 36.866J_4 = -18\,369.0 \qquad (5)$$

By using the Gause method, these equations can be solved: $J_1 = 1429.42\ Wm^2$, $J_2 = 911.07\ Wm^2$, $J_3 = 675.44\ Wm^2$ and $J_4 = 516.53\ Wm^2$, respectively. So that the radiant heat emission from the stove can then be calculated by:

$$Q_{sr} = Rs_1^{-1}(Eb_1 - J_1) = 1.152.(4929.27 - 1427.42) = 4.034\ kW \qquad (6)$$

And the convective emission from the stove may be predicted by reducing the Q_{sr} from the total stove output (5.5 kW), which gives Q_{sc} = 1.466 kW. On the other hand, from the steady-state measurement of air flow across the stove, it has been found that the air flow rate and temperature increase are about 4.1 dm^3s^{-1} and 245°C, respectively. Thus the convective heat emission from the stove based on the rough test will be about 1.2 kW. It seems that the prediction of radiant heat transfer is good.

In considering the foregoing analysis, it has been found that the radiant heat emission from the stove takes about 73 % of the total heat output. It is evident that radiant heat transfer will be the dominant factor for the internal surface temperature and then the temperature distribution within the sauna. As a consequence, if an even temperature distribution is required in the sauna, the hot stone surface on the stove must be 'seen' by each surface space. Another conclusion is that if the stove is elevated above the floor, the temperature in the zone lower than the stove's upper surface can be very low. The configuration and position of the sauna stove becomes the dominant factor in controlling the sauna room temperature distribution. Further detailed research on the sauna stove may be required in the future.

Air flow within the sauna in consideration

There are two interesting cases to be considered: one is that the fresh air is delivered into the sauna at the high-level side wall above the stove; the other is that the fresh air is delivered into the sauna at the low-level side wall below the stove. For both cases, the exhaust inlet is positioned at the opposite wall 1890 mm above the floor.

Table 2. Boundary conditions

	Ceiling	*Floor*	*Upper walls*	*Lower walls*			*Stove*	
					L.R. Wall	*F.B. wall*	*Lower surface*	*Upper surface*
Case 1 (high level air supply)	80.5°C	35°C	80°C	35°C	72.5°C	70.7°C	60°C	1600 Wm^2
Case 2 (low-level air supply)	80.5°C	35°C	75°C	50°C	72.5°C	70.7°C	60°C	1400 Wm^2

The fresh air temperature is 20°C and the air flow rate is 48 kg/h. The boundary conditions are considered in such a way that the ceiling, floor, upper side walls (above the stove upper edge) and lower side walls have different temperatures, but the temperature for each region is the same everywhere. The stove is considered separately. The boundary condition at the upper surface of the stove is set in heat flux (the convective part), whereas for the other surfaces in temperature. The detailed values for the boundary settings are listed in Table 2.

In fact all the boundary conditions are assumed or simplified based on the laboratory tests of a sauna [1]. Obviously, the boundary conditions in the simulated model are not exactly the same as in the tested sauna. e.g. even temperature distribution has been assumed for each region. However these kind of simplifications are reasonable, for example, the measured temperature difference between the ceiling and upper side walls are marginal.

The axial system in the simulations is shown in Fig. 2.

Air flow and temperature distribution in sauna in case 1

The temperature gradient in vertical direction of A–A section in Fig.1 has been measured for both cases. The calculated and measured profiles are shown in Fig.4. Agreement can be found in the lower and centre zones of the sauna. However, in the region near the ceiling, the temperature is underestimated. This error may have

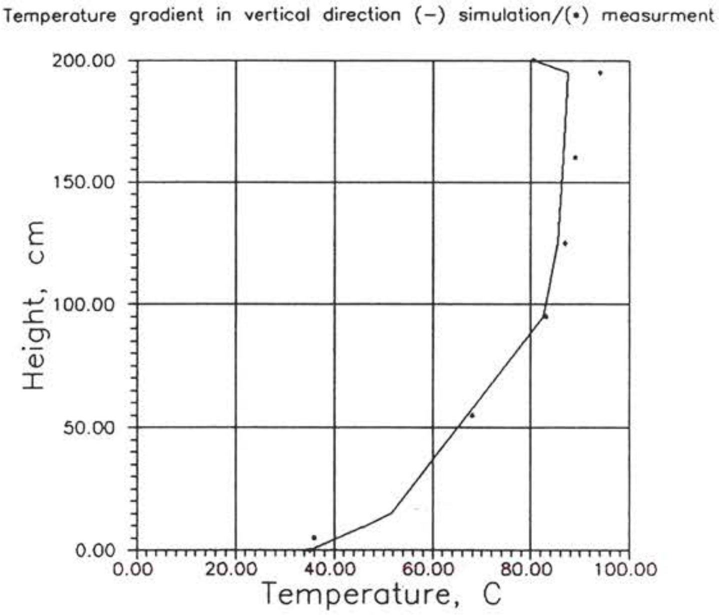
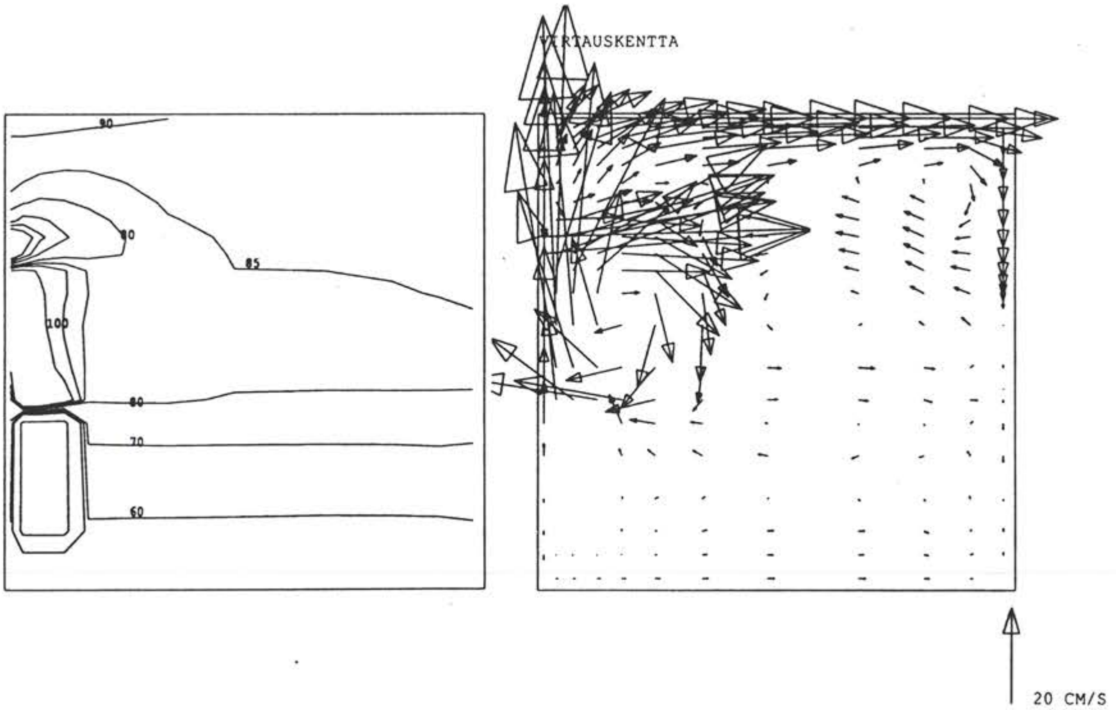


Fig. 4. Temperature gradient in vertical direction at the centre of section A–A.



Temperature °C **Velocity, cm/s**

Fig. 5. Air flow and temperature distribution at the section across the centre of air inlet and stove.

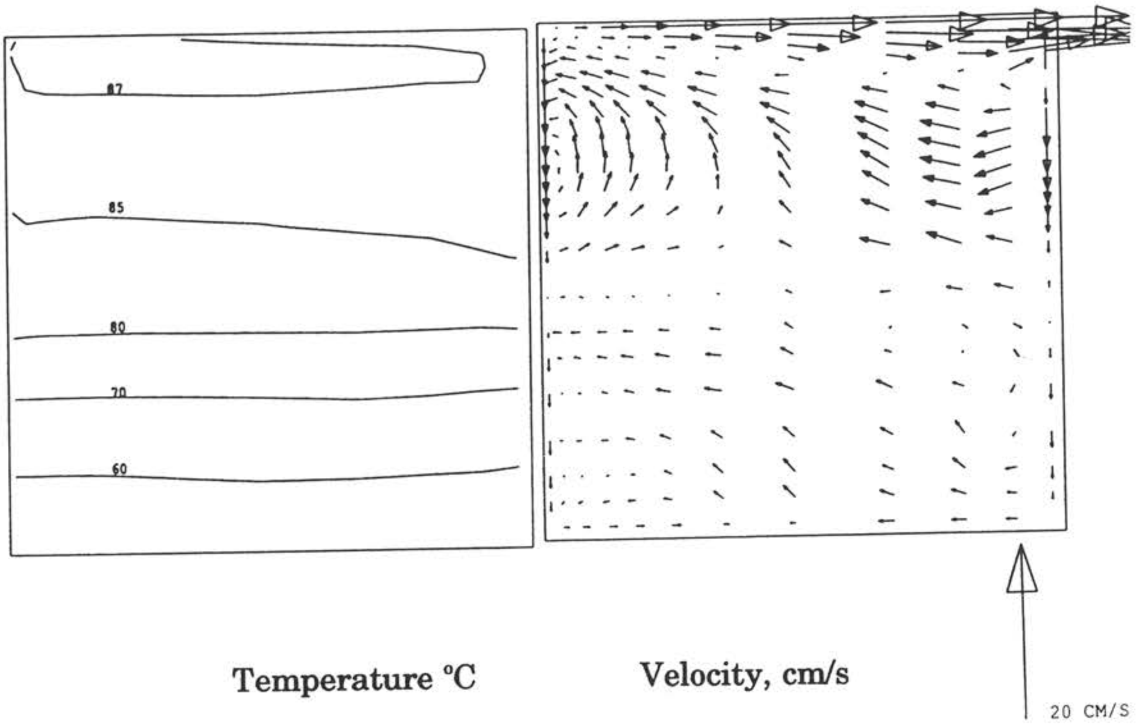


Fig. 6. Air flow and temperature distribution at the section across the centre of air outlet. (Note the scale of velocity is different from Fig.5).

arisen from the using of the wall function in WISH program and the simplified definition of boundary conditions in the simulated model. In addition, the buoyancy force generated by cold fresh air is against the buoyancy force generated by stove hot plume, which will cause difficulties for the WISH program in handling the mixing of air and dissipation of energy.

The other interesting places are the sections across the air inlet and stove as well as the air outlet. The air flow and temperature distribution of these two sections are shown in Fig.5 and Fig.6, respectively. The hot plume generated by the stove is so strong that the cold fresh air is brought up to the ceiling and the mixed air circulates around the ceiling until it is exhausted. The hot plume with a temperature of 100°C can be kept to the height about 0.6 m above the stove, which agrees with the steady-state measurement. Air flow, in fact, can be divided into upper-zone air flow and lower-zone air flow. The lower-zone air flow is too slow to be detected. Air outlet has moderate effect on its near region.

Air flow and temperature distribution in sauna in case 2

In the traditional design of a sauna, the fresh air is delivered into the sauna from the place just below the stove or from the low-level side wall. In this simulation the fresh air is delivered into the sauna below the stove. The comparison between measured and calculated results is also made for this case with respect to the temperature gradient in vertical direction at the centre of section A–A (see Fig.7). There is good agreement between the measured and calculated results.

Air flow and temperature distribution at the sections across air inlet/stove and air outlet are shown in Fig.8 and Fig.9, respectively. Air flow is also divided into upper-zone and lower-zone flow caused by hot plume and fresh air supply separately. Fresh air flow quickly slows down and loses its momentum. Whereas the hot plume is much stronger than that in case 1. This flow pattern will explain why the temperature gradient in vertical direction for this case is very large. Another interesting finding is that the temperature gradient near the floor becomes negative, i.e. the floor surface temperature is higher than that of the air nearby.

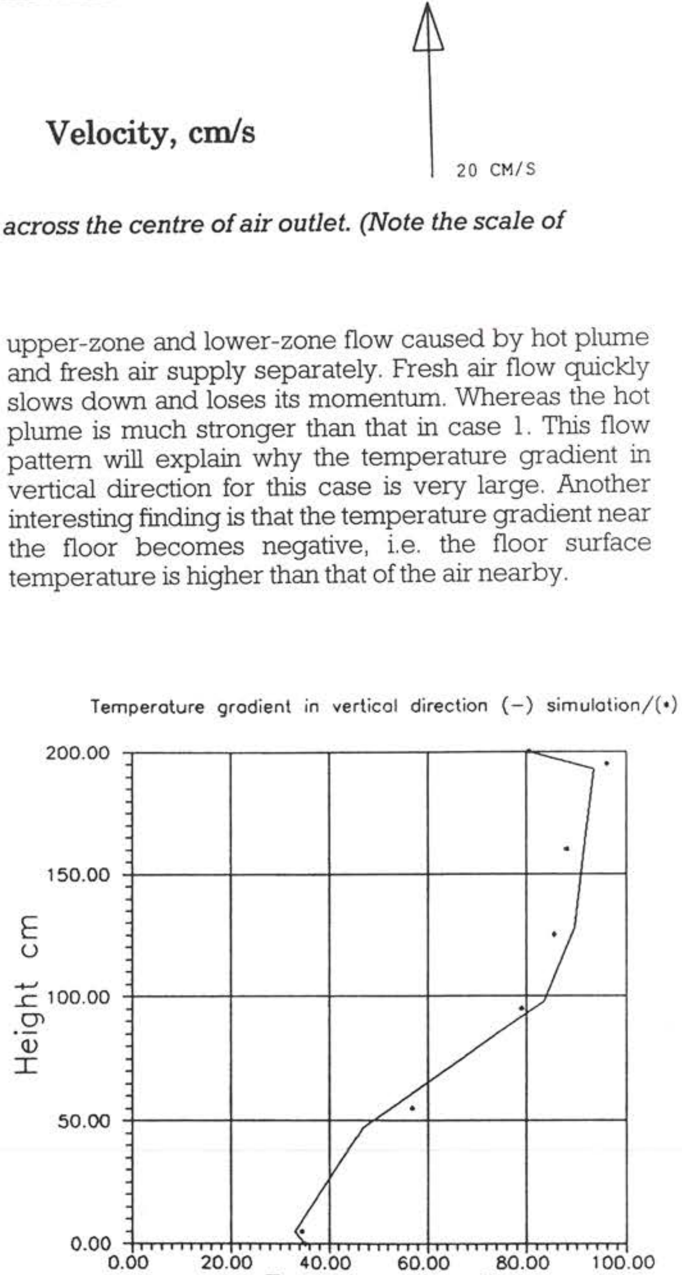


Fig. 7. Temperature gradient in vertical direction at the centre of section A–A.

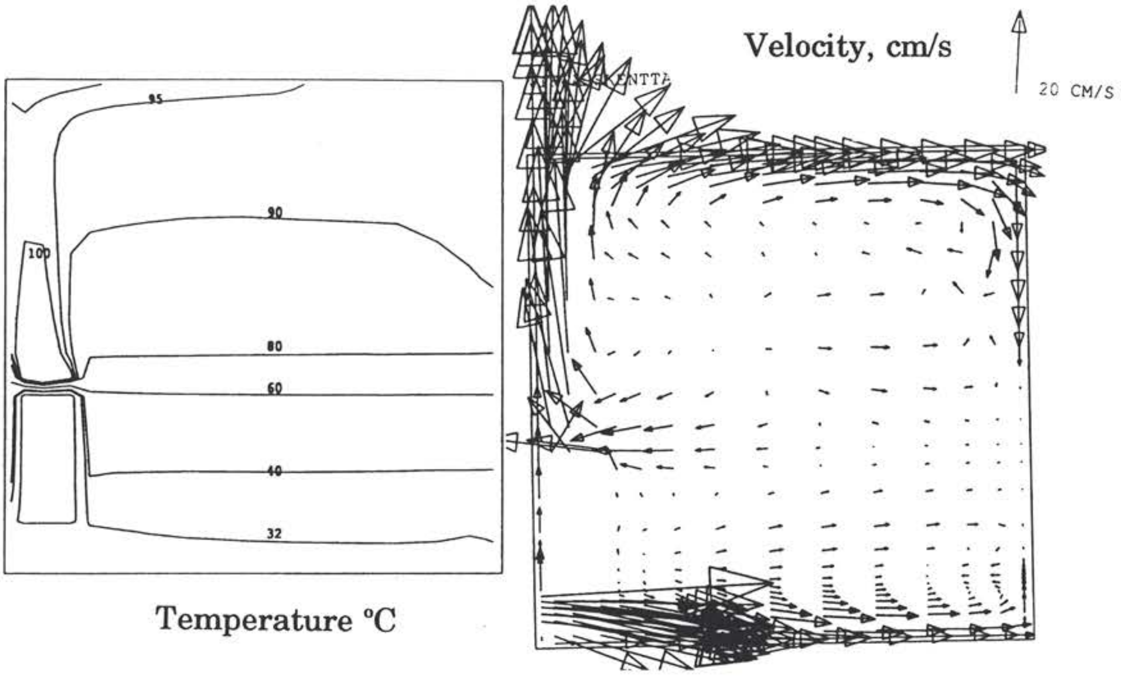


Fig. 8. Air flow and temp. distribution at the section across the centre of air inlet and stove.

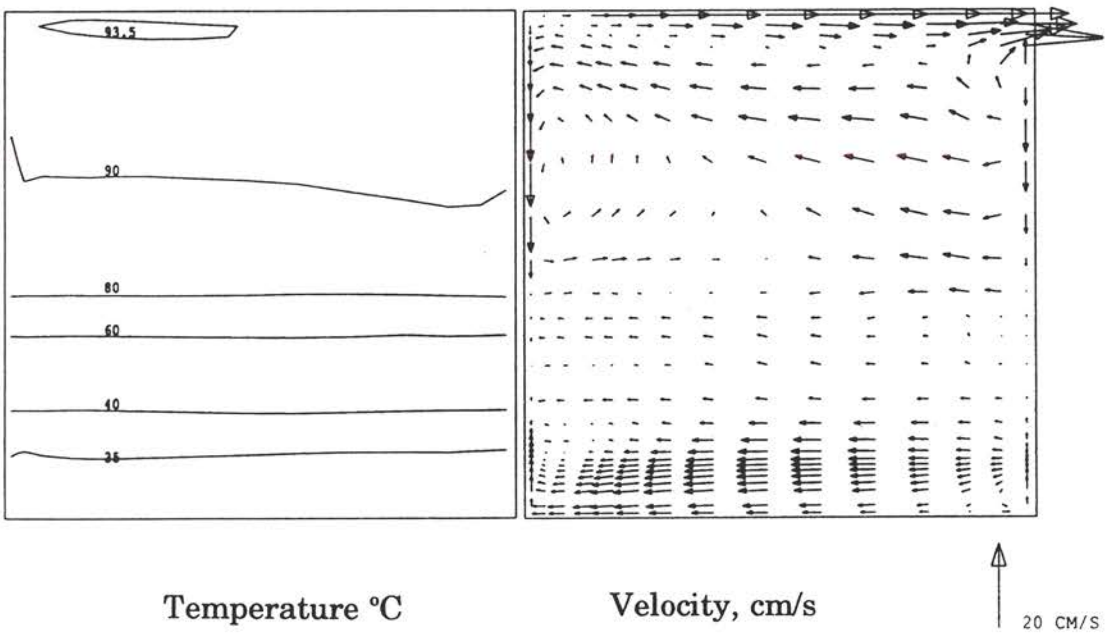


Fig. 9. Air flow and temperature distribution at the section across the centre of air outlet.

Conclusion

From the foregoing simulation and analysis, it has been found that the position of the air inlet has a great influence on the air flow and temperature distribution within the sauna. If a more even temperature distribution in the sauna is desired, then it would be better to deliver the fresh air into the sauna from a high level. It is evident that the buoyancy force of the relatively cold fresh air provides resistance against the upward hot plume when air is supplied into the space at a high level. However, defining lower surface temperature in relation to the lower side walls for case 1 (with high level side wall air supply) and higher surface temperature for case 2 (with low level side wall air supply) creates better agreement between the calculated and measured temperature distribution. This consequence cannot be explained by the current research. In comparison with smoke test [1], the simulated air flow patterns at the section across the centre of air inlet/stove is fairly good for both cases. In case 1, the hot plume is so strong that it can blow the supply air upward and then flow across the ceiling, whereas in the region lower than the stove, the air flow is very slow. In case 2, it seems that the air flow caused by the hot plume in the upper zone and the air flow caused by supply air in the lower zone are 'totally' separated. The delivered air quickly loses its momentum when blown in, and then climbs up at the opposite side wall to the neutral zone (stuffy zone) where it will be brought back into the stove slowly. The temperature gradient near the floor in case 2 can be negative. This may be explained by the combination of radiant heat exchange with hot upper sauna surfaces and convective heat transfer with cold fresh air nearby.

The calculation of radiant heat transfer between stove and sauna surfaces gave us the impression that radiant heat exchange is the dominant mechanism. In addition, even a simple model as shown in Figs. 2 and 3 can make it possible to predict fairly accurately the radiant heat transfer in a sauna. This finding offers us a means of reconsidering the current sauna stove design as well as the position in sauna from the view point of indoor air flow and temperature distribution within a sauna.

In this research, although only two cases have been considered, a closer look is offered into the air flow in a sauna. It should be mentioned that all the foregoing simulations haven't taken into account water evaporation. Further researches with respect to air flow, moisture transfer and radiant heat exchange are required so as to make possible better design of both sauna and sauna stove.

References

1. Äikäs E. and Holmberg R. (1992) Saunan lämpötilat ja ilmanvaihto (Temperature and ventilation of sauna). VTT report No.1431.
2. Lemaire T. (1990) *User manual of WISH.* TNO-Institute of Applied Physics.
3. Heikkinen J. (1991) *Modelling of a supply air terminal for room air.* Twelfth AIVC Conference, Vol. 3.
4. Chen Q.Y. (1988) Indoor airflow, air quality and energy consumption of buildings. Ph.D. Thesis, Delft Technical University.