EVALUATION OF INDOOR ENVIRONMENT IN VERNACULAR DWELLINGS
—NUMERICAL ANALYSIS OF THE IGLOO BY CFD—

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Summary

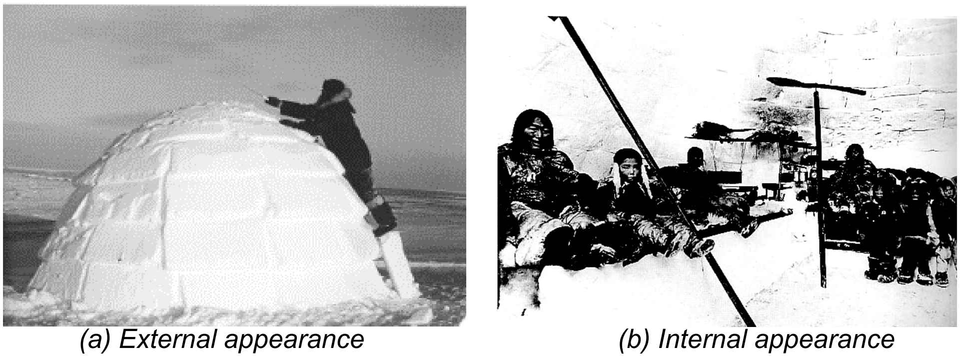
In this study, the indoor environment of an igloo, a type of vernacular dwelling, is analyzed by coupled numerical analysis using CFD. Vernacular dwellings incorporate effective techniques to improve the quality of the indoor environment, as well as to reduce the environmental impact. It is therefore possible to utilize their design concepts in the making of modern dwellings, especially when designing environmentally symbiotic housing. The results of numerical analysis are as follows: 1) With many sophisticated techniques, the internal temperature in an igloo can be raised to 12°C or more, when the outside temperature is –20°C. 2) The value of PMV in the living area is maintained at -0.3; clearly a little cold, but comfortable enough. 3) Indoor air quality is improved by making a small hole to allow for natural ventilation. Consequently, making full use of natural power, a good quality indoor environment can be built. It was also verified that CFD is a valid method to analyze the indoor environment in vernacular dwellings.

1. Introduction

Vernacular dwellings, with their variety of regional characteristics, fascinate many people, especially those who are involved in architectural design. Vernacular dwellings, i.e., traditional housing used in specific areas, have been identified as one model for sustainable buildings, because they possess the following characteristics:

1) In harmony with the climate, and built with local materials
2) Implementation of many sophisticated techniques to maintain a high-quality indoor environmental, making full use of natural power without depending on mechanical energy

However, there are few qualitative studies on the indoor environment in vernacular dwellings. In this study, the indoor environment in a vernacular dwelling is analyzed using computational fluid dynamics (CFD) with coupled simulation and radiation. We report on the thermal and air environment in an igloo (Figure1), a type of vernacular dwelling used in cold latitudes.[1]



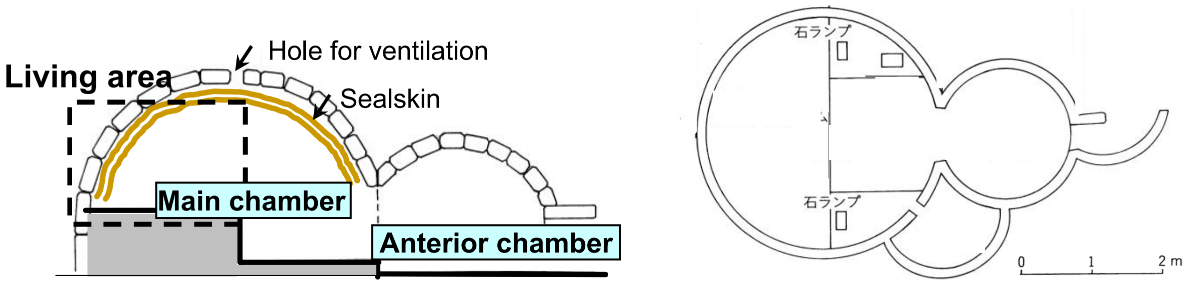
(a) External appearance *(b) Internal appearance*

Figure 1 Igloo

2. Evaluation of the Indoor Environment in an Igloo

2.1 Description of the Igloo

Igloos are winter dwellings used by the Inuit in the northern part of Canada where it is extremely cold. As Figure 2 shows, a typical igloo is composed of a main and an anterior chamber, the former serving as the area for living and sleeping, and the latter for preserving food. The igloo incorporates the following excellent techniques to keep the indoor thermal environment warm[2-7]. 1) The igloo is made of snow and includes plenty of foam, so that the insulation performance is pretty high. 2) The floor in the main chamber is higher than that in the anterior chamber; in addition the living space is created one step higher up in the main chamber. 3) The surfaces of the internal walls are covered with sealskin. 4) Usually the entrance is sealed with a snow block. 5) To improve the indoor air environment[6, 1)], a small hole for ventilation is made in the top of the dome wall, and it is pierced only when stale air has to be released.



(a) Cross-sectional view *(b) Plan view*

Figure 2 Igloo

2.2 Modeling

As shown in Figure 3, an igloo model was built with an emphasis on the above characteristics, which appear to contribute largely to the indoor environment. The size was based on the literature[2]. Following are details of the model. 1) The floor in the main chamber is 0.2 m higher than that in the anterior chamber, and the living area is 0.5 m higher than the main chamber. 2) The lower part of the entrance is sealed. (The aperture ratio of the entrance is 10 %.) 3) A hole for ventilation, 0.1 m in radius[2)], is made in the top of the main chamber.

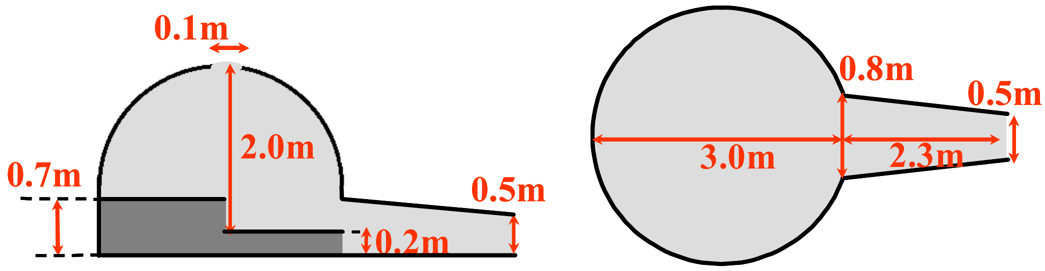


Figure 3 Analyzed model of an Igloo

2.3 Cases Analyzed

Five cases are analyzed in this paper. Figure 4 shows Model 1, which is a re-creation of an authentic igloo. Model 1 possesses the following characteristics. 1) Entrance is sealed by a snow block. (The aperture ratio is 10 %.) 2) Difference in floor level is created. 3) The surface of the internal walls is covered with sealskin. 4) The small hole for ventilation is closed.
The other models differ from Model 1 as shown in Table 1.

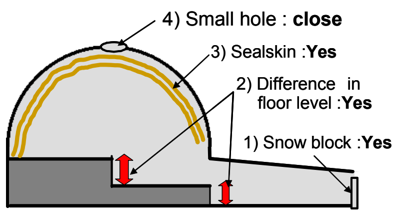


Figure 4 Model 1

Table 1 Cases analyzed

Cases Analyzed	1) Snow block	2) Difference in floor level	3) Sealskin	4) Small hole
Model 1	Yes	Yes	Yes	Closed
Model 2	**No**	Yes	Yes	Closed
Model 3	Yes	**No**	Yes	Closed
Model 4	Yes	Yes	**No**	Closed
Model 5	Yes	Yes	Yes	**Open**

3. The Indoor Thermal Environment

3.1 Outline of CFD Analysis

As shown in Figure 5, in this study the indoor environment in an igloo was analyzed by CFD with coupled simulation and radiation. Table 2 gives details of the CFD analysis.

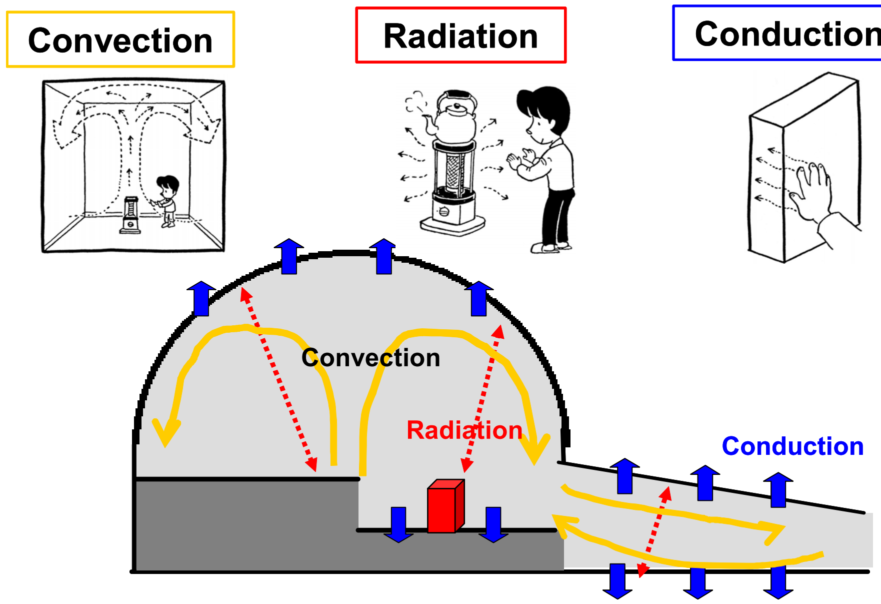


Figure 5

Table 2 Outline of CFD analysis

Turbulence model	High-Reynolds-Number k-e model
Algorithm	SIMPLE algorithm
Numerical schemes	First-order upwind difference scheme
Number of cells	160000

3.1.1 Model for analysis

As shown in Figure 6, a model of an igloo for analysis is placed at the center of a 3 m wide x 8 m long x 4 m high room. While the purpose was to evaluate the indoor environment in the igloo, both the indoor and outdoor environments are analyzed. This will enable the boundary conditions to be configured reasonably. The inlet and outlet are created on the opposite side to the entrance to the igloo. The inlet is located at the upper part, the outlet at the lower part.

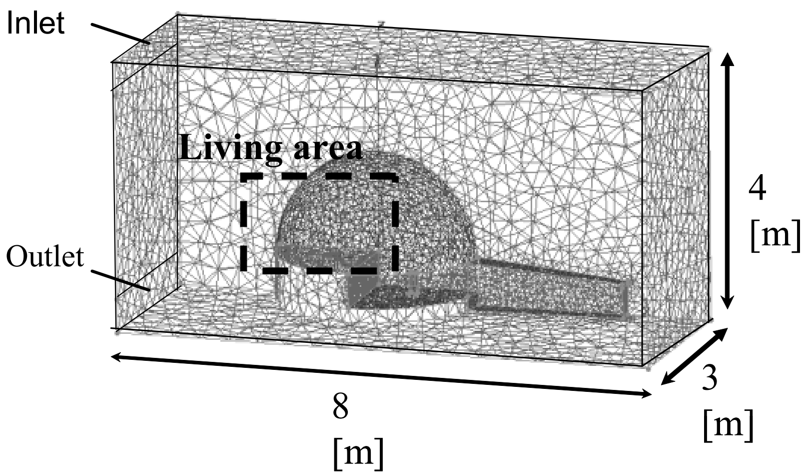


Figure 6 Analyzed model (shows half of the analyzed model for reasons of symmetry)

3.1.2 Boundary conditions for the numerical analysis

Table 3 gives the boundary conditions[8,9]. The outside temperature is set on the basis of the average temperature in winter in the northern part of Canada. The igloo is made of snow blocks 0.2 m wide. The surfaces of the internal walls in the main chamber are covered with sealskin and there is an airspace between the snow blocks and the sealskin. And a one-meter depth of snow is taken into consideration under the floor.

The heat condition appears in Figure 7. It is set with due consideration of the heating value of five residents (76 W/person) and that of two lamps[3] (150 W/lamp)[4]. 1) The heating value of the human bodies contributes to side A in the living area. However, in view of the thermal loss through the floor by heat conduction, only 85% of the heating value of the human bodies is considered to contribute to side A (90 W/m^2). 2) The heating value of the lamps contributes to B which is set at a lower level than side A.

Table 3 Boundary conditions

Inlet	Velocity : U_{in} = 0.356 m/s Temperature : T_{in} = -20°C Turbulence intensity : 10%, K_{in}=1.5(0.1Uin)^2 Turbulence length scale : l_{in} = 0.1 m ,ε_{in} = CμK_{in}3/2l_{in} (Cμ=0.09) Emissivity: 0.9	
Outlet	Velocity, temperature, k,ε: free-slip Emissivity : 0.9	
Walls of analyzed space (adiabatic faces)	Emissivity : 0.9 Velocity, temperature, k,ε: free-slip	
Wall surfaces of the igloo	Snow	Thermal conductivity : λ = 0.26 W/m･K[5] Emissivity : 0.1
	Sealskin	Thermal conductivity : λ = 0.08 W/m･K Emissivity : 0.96
	Airspace	Heat transfer resistance: R = 0.11 m^2･K/ w
Outdoor air	Heat transfer coefficient : 23 W/m･K	

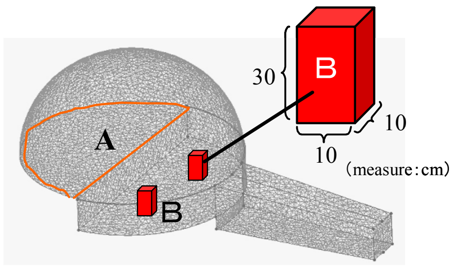


Figure 7 Heat condition

3.2 Results

Figure 8 shows the results for the temperature field for Models 1 to 5. Figure 9 shows the results for the velocity field for Models 1 and 5. As shown in Figure 8(a), the internal temperature in the living area of Model 1 can be raised to 12°C or more when the outside temperature is –20°C. When the small hole for ventilation is closed, the air change rate is only 0.4 times/hour because the entrance is the only ventilation opening. And as shown in Figure 8(a), the air circulation occurs in the anterior chamber. It is estimated from the result that the outdoor air has little effect on the living area.

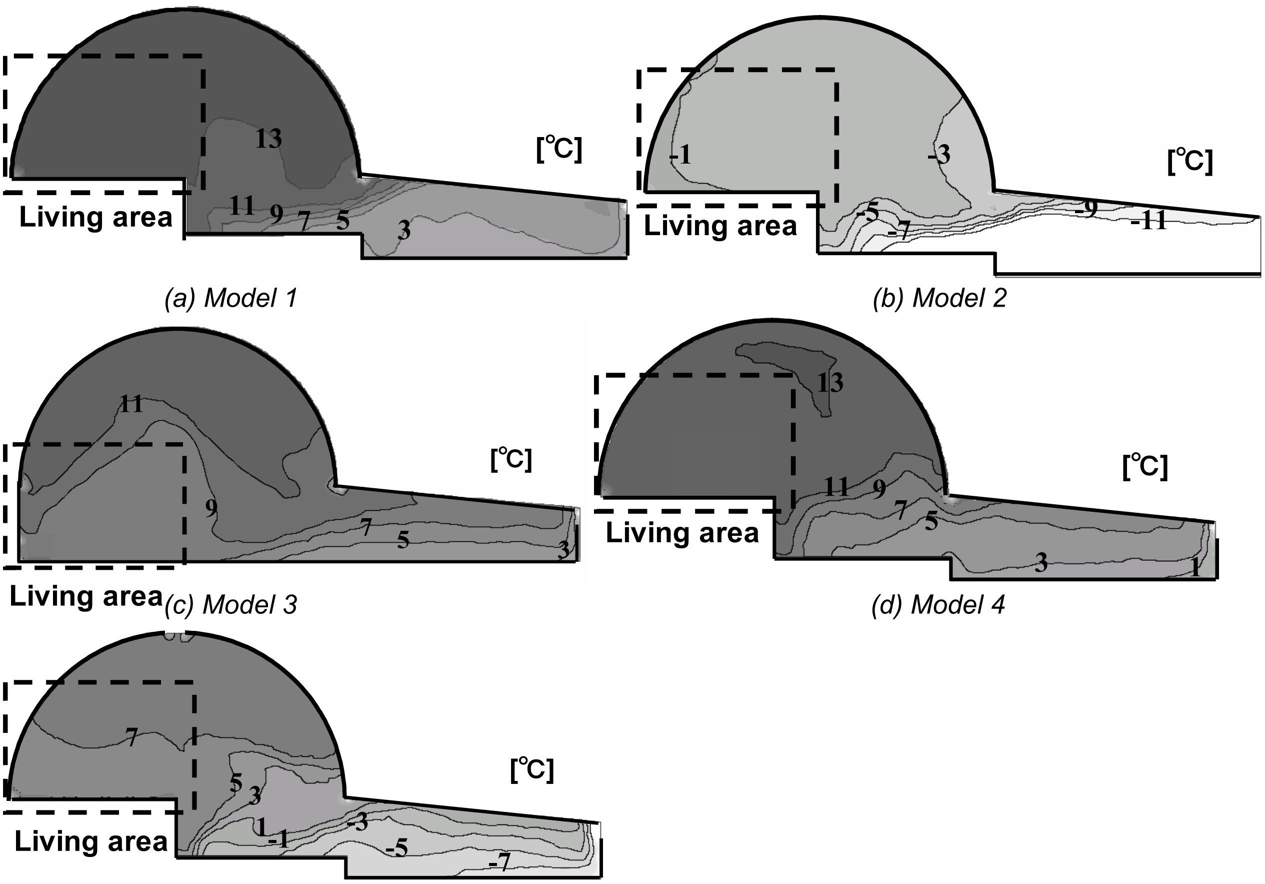
Next the effects of the change to the igloo's conditions are estimated in comparison with Model 1.

In the case of Model 2, shown in Figure 8(b), the absence of any snow block results in a 10°C reduction in the temperature of the living area. Hence the outdoor air has a large effect on the living area in the fully open condition.

In the case of Model 3, shown in Figure 8(c), the absence of any difference in floor level results in a 5 to 6°C reduction in the temperature in the living area. The temperature distribution in the igloo is utilized effectively to maintain a high temperature in the living area and a low temperature in the food storage area.

In the case of Model 4, shown in Figure 8(d), the absence of a sealskin lining results in a 2 to 3°C reduction in the temperature in the living area. This demonstrates how effective the sealskin lining is in keeping the indoor thermal environment warm.

In the case of Model 5, shown in Figure 8(e), opening the ventilation hole results in a 7°C reduction in the temperature in the living area. As shown in Figure 9(b), the air enters from the entrance and flows out through the hole in the top. As a result it is considered that the influence of the outdoor air is extended to the living area and causes a reduction in the temperature in the living area.

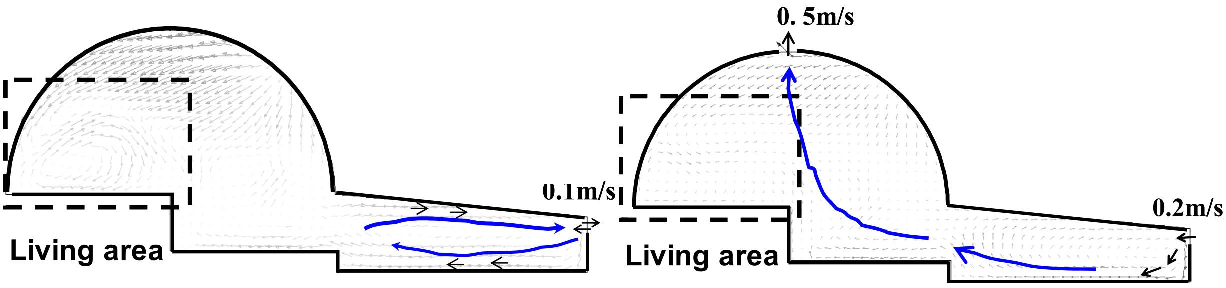


(a) Model 1 *(b) Model 2*

(c) Model 3 *(d) Model 4*

(e) Model 5

Figure 8 Temperature field



(a) Model 1 *(b) Model 2*

Figure 9 Temperature field

3.3 Calculation of PMV and PPD

Thermal amenity in the living area was evaluated by the comprehensive indicators for the thermal environment (PMV[6]) and the percent dissatisfied (PPD[6]). The following values were used for calculation of the PMV.

1) Air temperature, mean radiant temperature, relative air velocity: used analysis results
2) Clothing: 2.1 clo (refer to literature)
3) Activity level: 1.1 met

Table 5 gives the results. In the case of Model 1, the value of PMV in the living area is maintained at -0.3 and lies within the comfort region; clearly the living area is evaluated as a comfort area with respect to the thermal environment.

The other cases maintain the living area at -0.7 to -2.8 and are evaluated as too cold. They do not provide a comfortable indoor thermal environment.

Table 5 Values of PMV and PPD

Cases Analyzed	PMV	PPD
Model 1	-0.3	7
Model 2	-2.8	100
Model 3	-0.7	20
Model 4	-0.9	33
Model 5	-1.3	72

4. The Indoor Air Environment

4.1 Method

The air environment in the living area was considered from the representative viewpoint of smell[7]. For this evaluation, the olf[8] (odor emission rate) and the decipol[9] (the level of perception of odor) are used[10]. Expression (1) shows the relationship between the olf and the decipol. Expression (2) shows the relationship between the decipol and PD[10], the percentage dissatisfied.

$$C_i = C_0 + 36G/Q \qquad (1)$$

$$C_i = 112 \times [Ln(PD) - 5.98]^{-4} \qquad (2)$$

C_i : the perceived air quality in the designated area (decipol)
C_0: the perceived outdoor air quality (decipol)
Q : amount of ventilation in the designated area
G : total amount of olf in the target area

4.2 Results

Values for the decipol were calculated using Expression (1) for each model. The following values were used in the calculation of the decipol.
1) The perceived outdoor air quality *(C_0)* : 0 (Assumes no odorous substances outdoors)
2) The total amount of olf in the target area (G) : 5 olf (Assumes five person in the igloo)
3) The amount of ventilation (Q) : analysis results (as shown in Table 6)

Table 6 shows the values of the air change rate and PD for each model. The value of PD for Model 1 is 100%, and for Model 5 is 60 %. Thus the indoor air quality is inferior with the small hole closed, but is improved by opening the hole to allow for natural ventilation.

Table 6

Cases Analyzed	Air Change Rate (*amount of ventilation*)	PD [%]
Model 1	0.37 (0.6)	100
Model 2	10.1 (97)	24
Model 3	0.37 (4.8)	100
Model 4	0.39 (3.8)	100
Model 5	2.5 (24)	60

5. Overall Evaluation of Indoor Thermal and Air Environments

5.1 Method

The effects on the indoor thermal and air environments are considered in the overall evaluation. In the graph in Figure 10, the horizontal axis shows the percentage dissatisfied value for the thermal environment and the vertical axis shows the value for the air environment. The bottom left corner of the graph (the origin of coordinates) shows the best environment, and the upper right corner of the graph shows the most inferior environment.

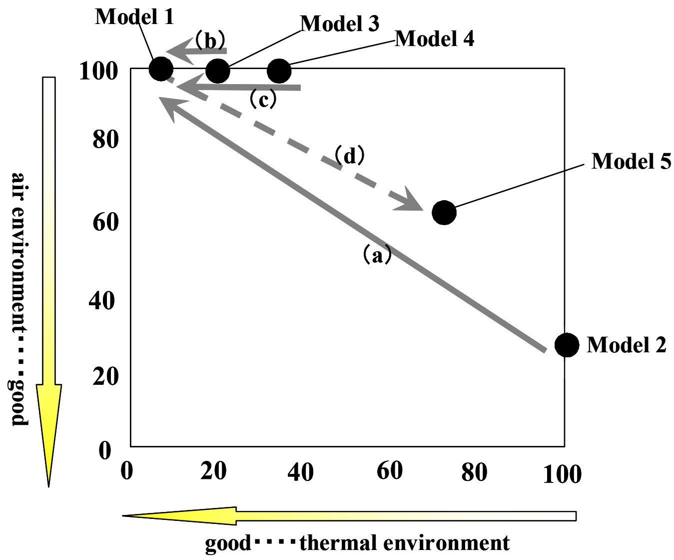


Figure 10

5.2 Discussion

In Figure 10, arrows (a) to (d) show changes in the thermal environment or air environment caused by the techniques used to change the environment as discussed. These changes in relation to arrows (a) to (d) are shown below.
(a) Closing the entrance (Model 2 → Model 1)
(b) Creating a difference in the levels (Model 3 → Model 1)
(c) Covering the surface of internal walls with sealskin (Model 4 → Model 1)
(d) Opening the ventilation hole (Model 1 → Model 5)
The thermal environment in the living area was improved by a large degree by closing the entrance, creating a difference in the floor level, and covering the surface of the internal walls with sealskin (Model 2, Model 3, Model 4 → Model 1). In this state, the indoor thermal environment in the living area is kept warm, but the air environment is very poor (Model 1). However, by making a small hole to allow natural ventilation, the indoor air quality is improved (Model 1 → Model 5). However with the hole kept open it is so cold that the indoor thermal environment cannot be maintained. This is why the hole should only be opened when the indoor air environment is poor.

6. Use of Natural Designs in Modern Architecture

6.1 Effective Utilization of Natural Power

With no mechanical energy, the internal temperature of the igloo could be maintained at 12°C or more, when the outside temperature was –20°C.
In the 20th century, the general trend is to maintain a high-quality indoor environment by the mass consumption of resources and energy. But it is clear that a comfortable indoor environment can be achieved with the use of natural power alone by using certain techniques.
The paradigm of mass production and mass consumption in the 20th century should be reconsidered from the point of view of sustainability. It is important to make full use of natural power by adopting green designs.

6.2 Homogeneous Environments and Nonhomogeneous Environments

Creating a difference in the floor level enables the igloo to be used for food storage where both the floor level and the temperature are low, and as a living area where both the floor level and temperature are high. This demonstrates that a nonhomogeneous environment can be used effectively by creating a big difference in temperature between the living area and other areas.
In the 20th century, control techniques that can equalize nonhomogeneous indoor environments have often been regarded as good engineering, and such designs often made use of mass energy and resources. But the effective adoption of green design techniques that is a requirement of the 21st century makes full use of natural power, making nonhomogeneous environments inevitable. Designs for nonhomogeneous environments that use less indoor environment equalization are important in reducing environmental impact.

7. Conclusions

(1) The indoor environment of an igloo was evaluated quantitatively using numerical analysis.
(2) The thermal environment in the living area can be maintained at an unexpectedly comfortable level. The air environment is poor but it can be improved by opening a ventilation hole.
(3) When the outdoor environment is extremely cold, it is not easy to maintain a high-quality indoor thermal environment as well as a good air environment at the same time. But implementing a combination of many techniques makes it possible to achieve a high-quality indoor environment.
(4) Making full use of natural power is an effective way to built a comfortable environment.

Notes

(1) It is said that igloos easily become full of offensive odors.
(2) The size is decided from the accuracy and man-hours needed to build an igloo.
(3) A receptacle filled with fuel and containing a wick. The fuel is often blubber.
(4) The heating value of a spirit lamp is about 200 W and so the value for the lamp in this case is taken as 150 W.
(5) The thermal conductivity of snow is proportional to its density. Considering the number of workers and the size of a snow block, the snow density is estimated at 0.2 g/cm^3. In fact snow blocks repeatedly melt and freeze when the igloo is in use. So in view of the reduction in the insulation efficiency, the snow density is taken as 0.35 g/cm^3.
(6) PMV means predicted mean vote. PPD means predicted percent dissatisfied.
The value of PMV was based on the judgment of the examinee and is a 7-point scale ranging from +3 to + -3 (+3: hot, +2: warm, +1: slightly warm 0: neutral, -1: slightly cool, -2: cool, -3: cold). A value in the range of -0.5 $< PMV < +0.5$ is suitable for a comfortable environment and the PPD is below 10%.
(7) The indicators of odor, the olf and decipol, were developed on the basis of environmental control in Northern Europe, and so the scale is hard to evaluate. In this case human bodies were considered as the source of emission of offensive odors, but there are other offensive odor emission sources, such as raw meat and excretory substances. So the air environment can be very bad.
(8) olf: a unit indicating the degree of air pollutants perceived by the human olfactory senses.
1olf can be defined as the amount of odor produced by a normal adult in an hour.
(9) decipol: the perceived degree of air pollutants
1 decipol can be defined as the level in an area with 1 olf where the air change rate is once per hour. (*The amount of ventilation is 36 m^3/hour*).
(10) The PD was based on an evaluation of the odor level in the experiment.
6 decipol indicates that the value of PD is 50%

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