J. Biol. Res. 2005 n. 1 - Vol. LXXX - Rubbettino - Soveria Mannelli

The effects of energy sources on the Iceman's low temperature storage conditions in the South Tyrol Museum of Archaeology

Roberto Bruttini[1], Marco Samadelli[2]

[1] Criofarma Freeze Drying Equipment, Strada del Francese 97/2L, 10156 Torino, ITALY E-mail: criofarma@tin.it
[2] Archaeological Museum of South Tyrol, via Museo 43, 39100 Bolzano, ITALY E-mail: marco.samadelli@iceman.it

KEY WORDS**:** Freeze Drying, Archaeological find, Iceman

Abstract

The conservation condition of the mummy of Similaun in the museum are presented and discussed in this work. Estimation of the effect of energy sources on the atmospheric freeze-drying process that can occur at low temperature conservation condition are also presented and discussed in this work. Experimental data of the effect of energy sources such as inspection windows, view lights, conservation cell walls and measuring equipments on the atmospheric freeze drying process are also discussed and quantified. Comparison of the experimental data with the theoretical model results are also discussed and the comparison shows that the agreement between experimental data and theory is good. The numerical solution of the non linear partial differential equations of the model proposed would allows model simulations that could indicate operative conditions and control strategies that could provide optimal long term conservation conditions of the man of Similaun and could lead to a series of novel conservation conditions of archaeological find in the museum.

Introduction

In 1991 the world was electrified by the chance discovery of an «Iceman» (the Man of Similaun) trapped in a glacier in the Otztaler Alps on the Austrian-Italian border. The corps was almost perfectly preserved; preliminary tests showed that indeed this was the body of a Neolithic hunter who died some 5300 years ago.
Several research activities on the Ice-man have been performed (Platzer et al., 1992; Spindler, 1994) and dynamic multi-dimensional models (Bruttini, 1998) has been used to study the conservation conditions of the Ice Man in the conservation cell in the Museum of Bozen, Italy, where the Man of Similaun is stored. Excellent results has been already obtained by using multi-dimensional mathematical models to predict the long time conservation process and make a reality the possibility to exhibit the mummy to the people visiting the Museum since May, 1998 (Bruttini, 1998).
The conservation cell is large enough to contain the mummy resting in a horizontal position on a trolley. The conservation cell is independently fitted with an efficient refrigeration plant and set to run at a constant temperature of minus 6,00 ± 0,10°C (Platzer et al., 1992). This is the annual mean temperature of the glacier at the Hauslabjoch, where it fluctuates between 0°C in summer and about minus 10°C in winter. The humidity in the conservation cell is kept at 98 ± 1% by means of the ice collected on the internal surfaces of the walls. The low temperature conservation cells is equipped with six temperature sensors. Two other electronically controlled sensors also monitor temperature and humidity. One of them lies directly against the body, the other is fitted to the chamber's inside wall. These transmit their readings to a computerized system which records every second and prints out data every minute around the clock. A continuous weighing system for the sample mummy is also present; this transmits its reading to a computerized system which also records every second and prints out data every minute around the clock. The electricity supply to the refrigeration chambers is backed up by batteries as a protection against power failure. A computerized alarm system is also present.
Estimation of the effect of energy sources of the atmospheric freeze drying process that can occur during the low temperature archaeological find storage in the museum are presented and discussed in this work. Comparison between experimental data and mathematical model results are also presented.

Theory

In Figure 1, a drawing of the system is shown. The body of the experimental mummy lies in a horizontal position on a

trolley placed in the centre of the conservation cell. All the six walls of the conservation cell are refrigerated at – 6°C and water is collected as ice on the internal surfaces of the close system. The cell is internally lightened by cold lights from the top and the inspection window allows the view of the mummy from outside. The shape of the experimental mummy has complex geometry (the legs and arms are in the shape of a cylinder; the head is in a shape of a sphere; the bust is in the shape of an elliptic cylinder) and, therefore, a simplified geometry for the body is taken (parallelepiped) as indicated in Figure 2 as first approximation for the investigation of the conditions inside the conservation system.
The following assumptions are made in the development of the mathematical model (Bruttini, 1998): (1) the thickness of the interface is taken to be infinitesimal (Liapis et al. 1994, 1995a, 1995b, 1997); (2) at the interface, the concentration of water vapour is in equilibrium with the ice (Liapis et al. 1994, 1995a, 1995b, 1997); (3) the ice is considered to be homogeneous, of uniform thermal conductivity, density and specific heat, and to contain a negligible portion of dissolved gas (inerts).
The continuity equation for the water vapour in the conservation cell, the water vapour mass flux components and the boundary conditions for the mass balance equations can be found in the reference (Bruttini, 1998)
The energy balance for the air in the cell is as follows:

$$\frac{\partial T_{air}}{\partial t} = \alpha_{air}\left(\frac{\partial^2 T_{air}}{\partial x^2} + \frac{\partial^2 T_{air}}{\partial y^2} + \frac{\partial^2 T_{air}}{\partial z^2}\right) - \frac{1}{\rho_{air}}\left(\frac{\partial\left(N_{w,x}T_{air}\right)}{\partial x} + \frac{\partial\left(N_{w,y}T_{air}\right)}{\partial y} + \frac{\partial\left(N_{w,z}T_{air}\right)}{\partial z}\right) + \frac{q_r}{\rho_{air}C_{p_{air}}} \quad (1)$$

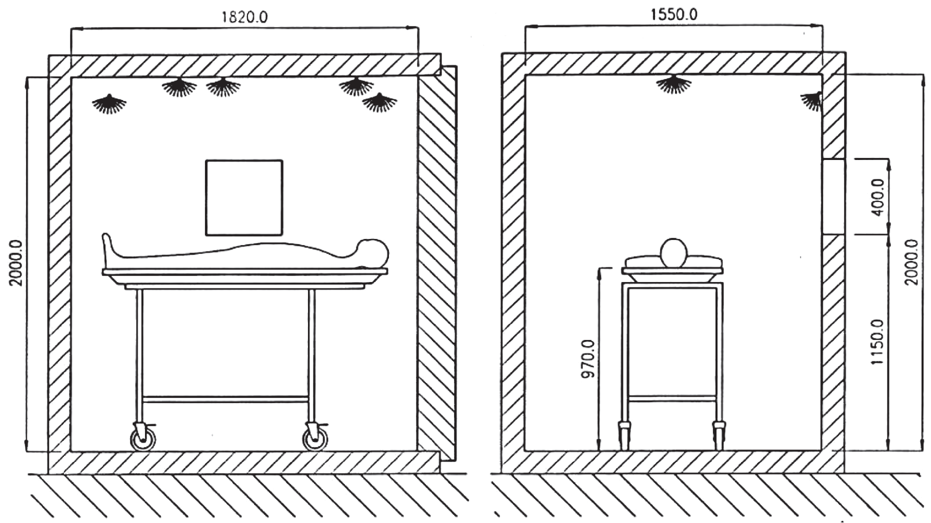

Fig. 1 - Low temperature conservation cell (-6°C) with controlled humidity.

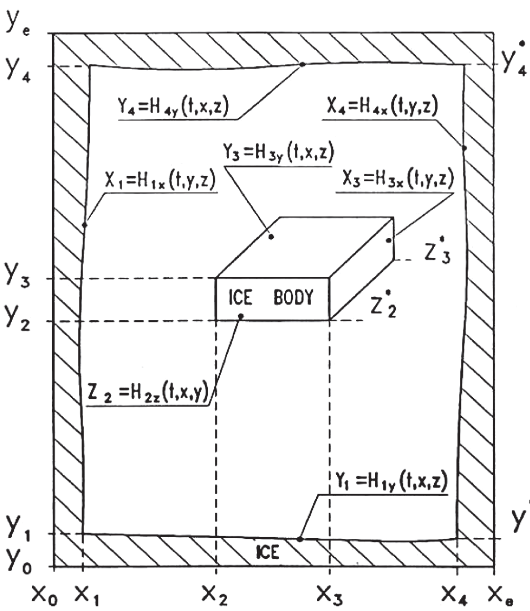

Fig. 2 - Diagram of the conservation cell and ice body.

where $\alpha_{air} = k_{air}/\rho_{air}$ and q_r is the net flux of radiant transfer between the gas at temperature T_{air} and: i) the surface area of the ice on the walls of the conservation cell, ii) the surface area of the ice on the body inside the conservation cell, iii) the surface area of inspection window and cold lights inside the conservation cell at temperature $T_{ice,wall}$, $T_{ice,body}$ and T_{iw} respectively.
The energy balance of the ice of the body as well as the ice on the walls of the conservation cell can be written as follows:

$$(2) \quad \frac{\partial T_{ice}}{\partial t} = \alpha_{ice}\left(\frac{\partial^2 T_{ice}}{\partial x^2} + \frac{\partial^2 T_{ice}}{\partial y^2} + \frac{\partial^2 T_{ice}}{\partial z^2}\right)$$

where $\alpha_{ice} = k_{ice}/\rho_{ice} C_{ice}$. The energy balance at the moving interface between the air and the ice in the conservation cell (ice on the six walls of the cell) is as follows (here given for the surface $X_1 = H_{1x}(t,y,z)$):

$$(3) \quad h_{rc}\left(T_{cell} - T_{ice}\right) - k_{ice}\left(\left(\frac{\partial T_{ice}}{\partial x}\right) - \left(\frac{\partial T_{ice}}{\partial y}\right)\frac{\partial H_{1x}}{\partial y} - \left(\frac{\partial T_{ice}}{\partial z}\right)\frac{\partial H_{1x}}{\partial z}\right)$$

$$+\left(\frac{dX_1}{dt} - \frac{\partial H_{1x}}{\partial y}\frac{dy}{dt} - \frac{\partial H_{1x}}{\partial z}\frac{dz}{dt}\right)\left(\rho_{ice} C_{p_{ice}} T_{ice} - \rho_{air} C_{p_g} T_{air}\right) = \left(C_{p_g} T_{x_1} + \Delta H_s\right) N_w$$

where h_{rc} is the combined radiation plus convection heat transfer coefficient and T_{cell} is the temperature of the air in the enclosure used in the computation of h_{rc} (Geankoplis,C.J.1993).
$N_{w,x}$, $N_{w,y}$, $N_{w,z}$ are the water vapour man flux components in the x, y and z direction respectively.
The water vapour mass flux components can be obtained from reference (Bruttini, 1998).
The terms in Equations (3) is evaluated at the air-ice interface of the walls. The energy balance at the moving interface between the air and the ice body in the middle of the conservation cell is as follows (here given for the surface $Y_3 = H_{3y}$ (t,x,z)):

$$h_{rc}\left(T_{cell} - T_{ice}\right) + F_{iw}\sigma\varepsilon\left(T_{iw}^4 - T_{ice}^4\right) + F_{il}\sigma\varepsilon\left(T_{il}^4 - T_{ice}^4\right)$$

$$- k_{ice}\left(\left(\frac{\partial T_{ice}}{\partial y}\right) - \left(\frac{\partial T_{ice}}{\partial x}\right)\frac{\partial H_{3y}}{\partial x} - \left(\frac{\partial T_{ice}}{\partial z}\right)\frac{\partial H_{3y}}{\partial z}\right) \quad (4)$$

$$+\left(\frac{dY_3}{dt} - \frac{\partial H_{3y}}{\partial x}\frac{dx}{dt} - \frac{\partial H_{3y}}{\partial z}\frac{dz}{dt}\right)\left(\rho_{ice} C_{p_{ice}} T_{ice} - \rho_{air} C_{p_g} T_{air}\right) = \left(C_{p_g} T_{y_3} + \Delta H_s\right) N_w$$

where F_{iw} and F_{il} are the view factors between the ice body and the inspection window and the cold light, respectively. T_{cell} is the temperature of the air in the enclosure used in the computation of. The interface Y_3 could be moving with time; the velocity vector V of the interface is completely specified by a material balance at the moving interface which defines its velocity as in Equation (8) of reference (Bruttini, 1998). The components of the velocity vector V are the same defined by the Equations (9-11) of reference (Bruttini, 1998) with the right hand side evaluated at $y = Y_3$. The energy balance at the other five moving interfaces of the ice body are as indicated in Equation (4) with the equation terms evaluated at the surfaces X_2, X_3, Y_2, Z_2 and Z_3. The energy balance on the six walls of the conservation cell (i.e., on the surfaces X_0, X_e, Y_0, Y_e, Z_0 and Z_e is as follows:

Fig. 3 - The Iceman inside the conservation cell at the Temperature of -6.03°C and Humidity 99.42%.

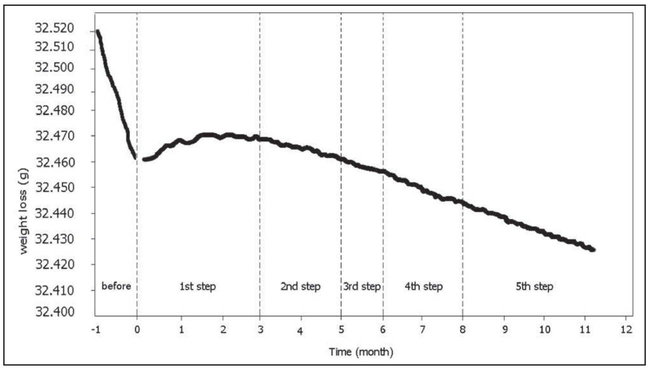

Fig. 4 - Calculated and experimental mummy weight versus time during the experimental study.

$$(5) \quad q_{wall} = h_{wall}\left(T_{cm} - T_{wall}\right)$$

where h_{wall} is the overall heat transfer of the cell wall while T_{cm} and T_{wall} are the cooling medium and wall temperature respectively.
The initial and boundary conditions are well specified in Equation (14-22) of reference (Bruttini, 1998).
Estimates of the time constant for the heat transfer from the walls and for mass transfer from the walls are estimated to be smaller than the heat transfer from the frozen layer of the body. Thus the heat transfer from the walls and mass transfer from the walls can be considered to be quasi steady state relative to the heat transfer from the frozen layer of the body

Results and discussion

The first result of the conservation condition indicated in reference (Bruttini, 1998) made so far possible the conservation of the Iceman and his exposure in the museum since May 1998 with an average of 300.000 visiting people every year. The scope of the archaeological museum of Southtyrol was to further improve the conservation condition of the Iceman with research activities devoted to minimize the effect of energy sources like the inspection window and illumination lights inside the cold (-6,00 ± 0,1°C) and humid (98 ±1%) conservation cell acting as driving forces on the potential atmospheric freeze drying process that could occur on the Iceman.

The effect of energy sources on the atmospheric freeze drying process that can occur at low temperature conservation condition has been studied by using experimental mummy. The experimental mummy used has similar dimension and weight as well as similar amount of free and bound water content and has been conserved in the same condition with respect to the temperature and humidity inside the experimental cell of the museum (Bruttini, 1998).

The result obtained are indicated in Figure 4. In the time period before the experimental study (indicated as before in Fig. 4) the average weight loss of the experimental mummy was 150 g/month constant for the last three months before the start of the experimental study.

The thickness of the ice walls of few millimetres before the experimental study has been increased up to 15 mm in all the six walls of the conservation cell, for all the experimental study presents in this work. The ice wall thickness has been built as an igloo form with purified and de-ionized water in all the six walls of the conservation cell. This new conservation condition led to an increasing of the total humidity inside the conservation cell (99,42% ± 0,15) as expected by the prediction on the dynamic behaviour of the mass transfer mechanism presented in the multi-dimensional model in reference (Bruttini, 1998) and led to an increasing in the air cell temperature stability (-6.030 ± 0,02°C).

Estimates of the time constant of the heat transfer from the walls and for mass transfer from the walls are estimated to be smaller that the heat transfer from the frozen layer of the body. Thus the heat transfer from the walls and mass transfer from the walls can be considered to be quasi steady state relative to the heat transfer from the frozen layer of the body.

The first step of the experimental study indicated in Figure 4 is represented by a period for stabilization of the new conservation system. The last part of this period where still the inspection window is heat insulated and close and the illumination lights are off is represented by the steady condition of the system where still a small amount of water is loss (4 g/month) because of the term $h_{rc}\,(T_{cell} - T_{ice})$ of equation (4) that can not be avoided because of the necessity conservation condition.

In the second step of the experimental study only the illumination lights where switched on with no effect on the weight loss that remain at 4 g/month. The term $F_{il}\sigma\varepsilon\,(T_{il}^4)$ - (T_{ice}^4) of equation (4) representing the radiation heat transfer from the illumination lights to the ice body can be, therefore, neglected without having significant effects in the computation of equation (4).

In the third step the illumination lights where switched again off with no effect as for the aim of the research activities of the museum devoted to reduce any thermal and radiation effects of the illumination lights.

In the fourth step only the inspection window of the close conservation cell was open to the external light and view.

In this step the total weight loss increased and is now at 6 g/month. The term $F_{il}\sigma\varepsilon\,(T_{il}^4)$ - (T_{ice}^4) can not be neglected as for model prediction and simulation. The value of the view factor F_{iw} has the same order of magnitude as the view factor indicated in reference (Gan 2004a, 2004b). The term $F_{il}\sigma\varepsilon\,(T_{il}^4)$ - (T_{ice}^4) representing the radiation heat transfer from the inspection window and the ice body is therefore very important but can not anymore be improved for the necessity of a good and safe view of the Iceman by the visiting people of the museum. The side effect of the inspection window is included in the computation of the combined radiation plus convection heat transfer coefficient $h_{rc.}$

In the last step the inspection window has been again close and heat insulated and the system returned to the original weight loss of 4 g/month as before the opening of the inspection window reaching again the original steady condition inside the system.

Conclusion

This is a model that could be applied for the low temperature conservation of the Iceman in the cell of the museum. The experimental data so far obtained during the experimental period are shown in Figure 4 where the influence and limitation of the energy sources at low temperature storage condition able to avoid long term atmospheric freeze drying process of the Iceman has been analyzed. The consistence of the multi-dimensional mathematical model with the experimental data so far obtained appears to be compatible and good. The model could indicate operative conditions and control strategies that could provide optimal long term conservation conditions of the man of Similaun.

The bound water it is a very important part of the Iceman since it is one of the components of the original living organism and it is bounded to the proteins and other original organic molecules. It must therefore be preserved.

Notation

C_{P_g}	heat capacity of gas at the free surface	kJ/kg•K
$C_{P_{ice}}$	heat capacity of ice	kJ/kg•K
H_{ni} (t,j,k)	function of free surface	n=1,...,4;i,j,k=x,y,z;i#j#k
k_{air}	air thermal conductivity	W/m•K
k_{ice}	ice thermal conductivity	W/m•K
γ (T)	functional expression of the thermodynamic equilibrium between the water vapour and the ice at the temperature, T, of the moving sublimation interface,	$T(p_w = \gamma\,(T))$, N/m^2
ΔH_s	heat of sublimation of ice	kJ/kg
air	density of air in the experimental cell	kg/m^3
ice	ice density	kg/m^3

Literature Cited

Bruttini R. 1998. Dynamic multi-dimensional models of the atmospheric freeze-drying process that can occur during the low temperature archaeological find storage in the museum: a study on the conservation conditions of the man of Similaun, Proceedings of the 11th International Drying Simposium, vol.C, p. 1849-1856

Egarter Vigl E, Samadelli M, Fitchel G. 2000. The Iceman mummy in the archaeology museum of Southtyrol: development of a new method of conservation, World conference of mummies of Nuuk (Greenland)

Gan KH, Bruttini R, Crosser OK, Liapis AI,.2004a. The effects of tray side and drying chamber wall temperature on the performance of freeze drying in vials arranged in clusters of square and hexagonal arrays on trays for different heat input control policies, International Meeting on Pharmaceutics, Biopharmaceutics and Pharmaceutical Technology and EFCE Working Party on Drying, Nuremberg, Germany

Gan KH, Bruttini R, Crosser OK, Liapis AI. 2004b. Heating Policies during the primary and secondary drying stages of the lyophilization process in vials: effects of the arrangement of vials in clusters of square and hexagonal arrays on trays, Drying Technology (in press).

Geankoplis CJ. 1993. Transport Processes and Unit Operations, Prentice- Hall, Inc. U.S.A. New Jersey, Englewood Cliff.

Liapis AI, Bruttini R. 1994. A theory for the primary and secondary drying stages of the freeze drying of pharmaceutical crystalline and amorphous solutes: comparison between experimental data and theory, Separations Technology, 4, p. 144-155.

Liapis AI, Bruttini R. 1995a. Freeze drying of pharmaceutical crystalline and amorphous solutes in vials: dynamic multi-dimensional models of the primary and secondary drying stages and qualitative features of the moving interface, Drying Technology, Vol.13, p. 43-72.

Liapis AI, Bruttini R. 1995b. Freeze Drying, Handbook of Industrial Drying (second edition), A. S. Mujumdar (ed), Marcel Dekker, Inc., New York, U.S.A. and Basel, Switzerland, p. 309-343.

Liapis AI, Bruttini R. 1997. Mathematical Modelling and Numerical Techniques in Drying Technology, I. Turner and A. S. Mujumdar (ed), Marcel Dekker, Inc., New York and Basel, p.481-535.

Platzer W, Spindler K, Hopfel F. 1992. The Man in the Ice, University of Innsbruck, Innsbruck, Austria, Vol. I

Spindler K. 1994. The Man in the Ice, Weidenfeld and Nicolson, London, England