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The Design of a cooling table for conference services

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ABSTRACT

Refrigeration is the applied science which deals with reducing the temperature of a confined space and its content to a predetermined level that is below the ambient temperature. The design of a cooling table is presented. The cooling table is an innovative application in refrigeration system design. The table is a multipurpose table for maintaining a low product temperature whilst still being able to carry out other activities on the table like a conventional table. The design covers the compressor, condenser, evaporator, table frame, table top, cabinet volume and the covers. The prototype design requires a 70W compressor for three participants.

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Introduction

In the world today, virtually everything has been made easy for the comfort of man. It has been observed that people, especially in tropical countries, enjoy drinks more when it is chill. Refrigeration is the applied science which deals with reducing the temperature of a space and its content to a predetermined level that is below that of the surrounding [1].

The cooling table is an innovative application of refrigeration system. The cooling table is a multipurpose table for maintaining a low product (drinks) temperature while being able to carry out other activities on the table like a normal conference table. It is enclosed and lagged for maintaining a temperature of about 10°C which keep the drinks in a cold state as long as desired. The cooling table could be used at conferences, seminars, cocktail parties, general meetings, canteens, to mention a few. Despite environmental factors, the cooling table is properly lagged against external heat radiation as well as conductive and convective heat transfer.

The cooling table must fulfill the requirement for normal domestic refrigerating system in having adequate heat transfer surfaces, thus supplementing the use of refrigerators. Furthermore, it will be designed so that there is virtually no heat transfer to the table, thus satisfying the functional requirement of an ordinary table.

The main objective of this paper is to design a cooling table made from locally available materials that will accommodate other various activities while ensuring that drinks served to participants during conferences, meetings, and seminars remain chilled as long as the meeting lasted.

The Refrigeration Cycle

Using the Pressure-Enthalpy diagram and the Temperature-Entropy diagram in figure 1 and figure 2 respectively, the stages are thus; 1-2, saturated vapour enters the compressor. 2-2', Constant pressure heat removal from super-heated vapour at a high temperature and pressure. 2'-3', Isothermal condensation at a constant pressure. Heat is removed from the saturated vapour,

it turns to saturated liquid. 3'-3, the saturated liquid is sub-cooled at constant pressure. 3-4, Isenthalpic expansion of sub-cooled liquid refrigerant to lower temperature and pressure. 4-1 represents the Isothermal vaporisation of the wet vapour refrigerant to a saturated vapour state [1-3].

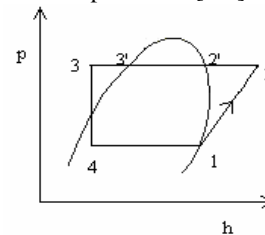


Figure 1: Pressure (p)-Enthalpy (h) Diagram

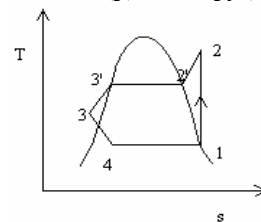


Figure 2: Temperature (T)-Entropy (s) Diagram

Design Analysis

The cooling table is made effective by the conventional domestic refrigeration components namely; compressor, condenser, capillary tube, filter dryer, thermostat and evaporator.

Evaporator Design and Analysis

Evaporator load (\dot{Q}_E) is the rate at which heat must be removed from the refrigerated space in order to attain and maintain the desired temperature. The evaporator load is made up: Usage load (\dot{Q}_U), Leakage load (\dot{Q}_L) and Supplementary load (\dot{Q}_S).

$$\dot{Q}_E = \dot{Q}_U + \dot{Q}_L + \dot{Q}_S \quad (1)$$

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$$\dot{Q}_U = mc(T_2 - T_1) \quad (2)$$

The supplementary load is defined as 15% of the usage load [4].

$$\dot{Q}_S = 15\% \text{ of } \dot{Q}_U = 0.15 \dot{Q}_U \quad (3)$$

Where, T_1, T_2, m and c are temperature of product leaving cooler, entering cooler, specific heat of product, mass flow rate of the refrigerant.

The leakage load (\dot{Q}_L), is the rate of heat transfer through the insulated walls as shown in figure 3.

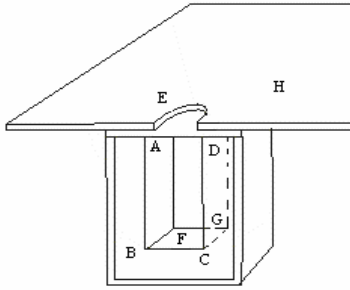


Figure 3: Diagram of Cooling Table Showing the Insulated Walls of a single port.

The rate of heat transfer through the surface ABCD

$$\dot{Q}_{ABCD} = A_1 U_1 \Delta T_1 = \frac{A_1 \Delta T_1}{\left(\frac{x_1}{k_1} + \frac{x_2}{k_2} \right)} \quad (4)$$

$$\dot{Q}_{ABCD} = \dot{Q}_{CDHG} = \dot{Q}_{ABEF} = \dot{Q}_{EFGH} \quad (5)$$

The rate of heat transfer through the surface ABCD, ABEF, CDHG, and EFGH is

$$4 \dot{Q}_{ABCD} = \frac{4 A_1 \Delta T_1}{\left(\frac{x_1}{k_1} + \frac{x_2}{k_2} \right)} \quad (6)$$

$$A_1 = AB \times BC \quad (7)$$

The rate of heat transfer through the surface BCGF

$$\dot{Q}_{BCGF} = \frac{A_2 \Delta T_2}{\left(\frac{x_1}{k_1} + \frac{x_2}{k_2} \right)} \quad (8)$$

$$A_2 = BC \times CG \quad (9)$$

The rate of heat transfer through cabinet cover

$$\dot{Q}_c = \frac{A_3 \Delta T_3}{\left(\frac{x_3}{k_3} + \frac{x_6}{k_2} + \frac{x_7}{k_1} \right)} \quad (10)$$

$$A_3 = \frac{\pi D^2}{4} \quad (11)$$

The total rate of heat transfer into the evaporator is

$$\dot{Q}_L = 4 \dot{Q}_{ABCD} + \dot{Q}_{BCGF} + \dot{Q}_c \quad (12)$$

Where x_1, x_7 = polystyrene thickness

x_3 = formica thickness

x_2, x_6 = wood thickness

k_1 = thermal conductivity of polystyrene

k_2 = thermal conductivity of wood

k_3 = thermal conductivity of formica

ΔT = change in temperature

U_1 = heat transfer coefficient

A_1, A_2 & A_3 = surface area of the respective lagging sides and the cabinet cover

D = diameter of port

\dot{Q} = rate of heat transfer

\dot{Q}_c = rate of heat transfer through cabinet cover

The length of the evaporator pipe for the refrigerant can be obtained using

$$\dot{Q}_E = A U \Delta T_f \quad (13)$$

Where, A and ΔT_f are surface area of the evaporator and Temperature difference between ambient and the fluid in the pipe respectively.

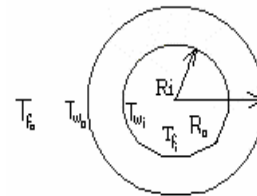


Figure 4. Cross Section of Evaporator Tube

For outside convection;

T_{fo} = temperature of fluid outside the pipe

T_{fi} = temperature of fluid in the tube

T_{wo} = temperature on the outside surface of the tube

T_{wi} = temperature on the inside surface of the tube

$$\dot{Q} = h_o \pi D_o L (T_{fo} - T_{wo}) \quad (14)$$

Therefore,

$$T_{fo} - T_{wo} = \frac{\dot{Q}}{h_o \pi D_o L} \quad (15)$$

For conduction in the tube wall;

$$\dot{Q} = \frac{2k\pi L (T_{wo} - T_{wi})}{\ln \frac{D_o}{D_i}} \quad (16)$$

Therefore,

$$T_{wo} - T_{wi} = \quad (17)$$

For inside convection;

$$\dot{Q} = h_i \pi D_i L (T_{wi} - T_{fi}) \quad (18)$$

Therefore,

$$T_{wi} - T_{fi} = \frac{\dot{Q}}{h_i \pi D_i L} \quad (19)$$

Adding equations(15), (17) and (19)

$$T_{fo} - T_{fi} = \frac{\dot{Q}}{\pi L} \left[\frac{1}{h_o D_o} + \frac{1}{2k} \ln \frac{D_o}{D_i} + \frac{1}{h_i D_i} \right] \quad (20)$$

But

$$\dot{Q} = \pi D_i L U (T_{fo} - T_{fi}) \quad (21)$$

From equation (20) and (21), the overall heat transfer coefficient is

$$U^{-1} = \frac{1}{h_i} + \frac{D_i}{2k} \ln \frac{D_o}{D_i} + \frac{D_i}{D_o h_o} \quad (22)$$

Where;

U = overall heat transfer coefficient

h_o = outside heat transfer coefficient

h_i = inside heat transfer coefficient of the evaporator

D_o = outside diameter of the evaporator tube

D_i = inside diameter of the evaporator tube

k = thermal conductivity of air [5].

The heat transfer coefficient, h_i for fluid flowing inside the tubes, the general Nusselt equation is

$$Nu = C(Re)^n (Pr)^m \quad (23)$$

Where, n and m are exponents. The constant C and exponents in the equation are defined by the Dittus-Boelter [3] equation

$$Nu = 0.023(Re)^{0.8} (Pr)^{0.4} \quad (24)$$

$$Nu = \frac{hD}{k_R} \quad (25)$$

$$Re = \left(\frac{\rho V D_i}{\mu} \right) \quad (26)$$

$$Pr = \left(\frac{\mu c_p}{k} \right) \quad (27)$$

Equations (24), (25), (26) and (27) can be expressed in a non-dimensional form.

$$\frac{hD}{k_R} = 0.023 \left(\frac{\rho V D_i}{\mu} \right)^{0.8} \left(\frac{\mu c_p}{k} \right)^{0.4} \quad (28)$$

Where;

Nu = Nusselt number

Re = Reynolds number

Pr = Prandtl number

h = convection coefficient, W/m^2K

$D_i = D$ = inside diameter of tube, m

$k_R = k$ = thermal conductivity of fluid, W/mK

V = mean velocity of fluid, m/s

ρ = density of fluid, kg/m^3

μ = dynamic viscosity of fluid, $Pa.s$

c_p = specific heat capacity of fluid, J/kgK

From equation (25)

$$h_i = \frac{Nu k_R}{D_i} \quad (29)$$

$$h_o = \frac{Nu k_{air}}{D_o} \quad (30)$$

From equation (13),

$$\dot{Q}_E = (\pi D_i L) U \Delta T_f \quad (31)$$

Where $\pi D_i L$ is the surface area of the tube.

Therefore,

$$L = \frac{\dot{Q}_E}{\pi D_i U \Delta T_f} \quad (32)$$

Where, L and n are the length of coil for a single port and number of ports respectively.

The total length is given as

$$L_T = nL + (n-1)L' = \frac{n \dot{Q}_E}{\pi D_i U \Delta T_f} + (n-1)L' \quad (33)$$

L' is length of evaporator coil between two ports.

The volume of evaporator tube, V_e

$$V_e = \frac{\pi D_i^2}{4} L_T \quad (34)$$

Cabinet volume = cabinet cross sectional area x depth

$$V_c = \frac{\pi D_c^2}{4} h \quad (35)$$

For n number of cabinets,

$$V_c = \frac{n \pi D_c^2}{4} h \quad (36)$$

Condenser Design and Analysis

The condenser in a vapour compression refrigeration cycle is that which accepts high pressure-high temperature superheated gaseous refrigerant from the compressor, taking super heat away from it until it becomes saturated gas. The latent heat of the refrigerant is further removed from the saturated gas until it becomes saturated liquid. The heat rejected from the refrigerant is carried away by a different medium, which gives rise to different type of condensers. The finned tubing natural convection condenser was used in this paper.

Recall equation (22), (29) and (30)

$$U^{-1} = \frac{1}{h_i} + \frac{D_i}{2k} \ln \frac{D_o}{D_i} + \frac{D_i}{D_o h_o} \quad (22)$$

$$h_i = \frac{Nu k_R}{D_i} \quad (29)$$

$$h_o = \frac{Nu k_{air}}{D_o} \quad (30)$$

$$Nu = 0.023 Re^{0.8} Pr^n \quad (24)$$

Since cooling is effected, $n = 0.4$

$$Re = \frac{V D_i}{\nu} \quad (37)$$

Where ν = kinematic viscosity, V = velocity of flow

But

$$m = \rho V A \quad (38)$$

$$A = \frac{\pi D_i^2}{4} \quad (39)$$

Where

ρ = density of refrigerant,

A = cross sectional area of pipe

m = mass flow rate of the refrigerant

From equation (38) and (39)

$$V = \frac{\dot{m}}{\rho A} = \frac{4 \dot{m}}{\rho \pi D_i^2} \quad (40)$$

Equation (37) becomes

$$Re = \frac{4 \dot{m}}{\pi D_i \rho v} \quad (41)$$

If $Re > 10,000$ then the fluid is turbulent, hence, the Dittus-Boelter equation is used to obtain the heat transfer coefficient inside the pipe.

The dimensions of the fins attached to the condenser are width (w), thickness (t) and length (L_f)

$$P = 2(w + t) \quad (42)$$

Where P = surface area of the fin (perimeter)

$$A = w \times t \quad (43)$$

Where A = the cross sectional area of the fin

Fin index,

$$m = \left[\frac{h_o P}{k_{steel} \times A} \right]^{1/2} \quad (44)$$

Heat transfer through a fin, Q_f is given by

$$Q_f = \eta_f a_f h_o \Delta T_m \quad (45)$$

$$a_f = P \times L_f \quad (46)$$

Where,

η_f = fin efficiency [3]

ΔT_m = logarithmic temperature difference

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \quad (47)$$

$$\Delta T_1 = T_2 - T_3 \quad (48)$$

$$\Delta T_2 = T_3 - T_3 \quad (49)$$

Therefore, number of fins, N_f

$$N_f = \frac{\dot{Q}_{23}}{\dot{Q}_f} \quad (50)$$

Where, \dot{Q}_{23} = the heat rejected by the condenser.

Length of finned condenser, L_f ;

$$L_f = \frac{N_f \times w}{2} \quad (51)$$

Volume of condenser tubing, V;

$$V = \pi D_i L \quad (52)$$

Where L = length of tube

Compressor Capacity Design Analysis

Compressor is the heart of the refrigeration system. It supplies gaseous refrigerant at super-heated condition (at high pressure and temperature).

The compressor removes refrigerant vapour from the evaporator and raises the pressure and temperature of the vapour to such values that it can be condensed by heat exchange with normally available condensing media. The hermetically sealed compressor type was used for this project.

The capacity (size) of compressor use in a vapour compression system depends on the mass flow rate of the refrigerant, the specific volume of the refrigerant at the compressor intake pressure and the volumetric efficiency of the compressor.

For an adiabatic process, the compressor size will be

$$w_c = \dot{m}(h_2 - h_1) \quad (53)$$

$$\dot{m} = \rho \dot{V}_s = \frac{\dot{V}_s}{v_1} \quad (54)$$

Where,

w_c = the rating of the compressor, W

\dot{m} = mass flow rate of the refrigerant;

v_1 = specific volume of refrigerant at compressor suction

ρ = density of refrigerant; \dot{V}_s = swept volume in m^3/s

Capillary Tube

This serves as an expansion or throttling valve in so many applications. Its function is to regulate the amount of refrigerant that is supplied to the evaporator. It also reduces the pressure of refrigerant entering the evaporator so that it will be vapourized at the desired low pressure by absorbing heat from the refrigerated space.

The design of a new refrigeration unit employing a capillary tube must select the bore and length of the tube so that the compressor and tube fix a balance point at the desired evaporating temperature. Final adjustment of the length is by "cut and try". A longer tube than desired is first installed in the system with the probable result that the balance point will occur at too low an evaporating temperature. The tube is shortened until the desired balanced point is reached[3, 6].

Performances

Refrigerating effect (q_E): is the quantity of heat that a unit mass of refrigerant absorbs from the refrigerated space in one cycle. It is expressed mathematically as

$$q_E = h_1 - h_4 \quad (55)$$

Compressor work (w_c): is the work done by the compressor in raising the temperature and pressure of the refrigerant vapour. It is expressed mathematically as

$$w_c = h_2 - h_1 \quad (56)$$

Heat of condenser (q_c): this is the heat usually lost to air by the refrigerant in the condenser. It is expressed as

$$q_c = h_2 - h_3 \quad (57)$$

Expansion work (w_E): since process 3 – 4 is a throttling process, there will be no work done, hence,

$$w_E = h_3 - h_4 = 0 \quad (58)$$

Refrigerating capacity (\dot{Q}_r): this is the rate at which heat can be removed the refrigerated space and is expressed as

$$\dot{Q}_r = \dot{m}(h_1 - h_4) \quad (59)$$

Coefficient of performance (COP): this is the ratio of the refrigerating effect to the compressor work. It is expressed as

$$COP = \frac{q_E}{w_c} = \frac{h_1 - h_4}{h_2 - h_1} \quad (60)$$

Where,

\dot{m} = mass flow rate of the refrigerant

h_g = enthalpy of the refrigerant at saturated vapour

h_f = enthalpy of refrigerant at saturated liquid

h_1 = enthalpy of refrigerant at compressor suction

h_2 = enthalpy of refrigerant at inlet of the condenser

$h_{2'}$ = h_g at $40^\circ C$; $h_{3'}$ = h_f at $40^\circ C$

h_3 = enthalpy of refrigerant entering the capillary tube

h_4 = enthalpy of refrigerant at entry to the evaporator [6].

Auxiliary Components

The auxiliary components such as the thermostat and filter/dryer used in this paper were not designed but rather sourced from the market to suit the design of the other components.

The Table Components Design

There are various table designs used for conferences, meetings, restaurant services and the likes. The design depends on the seating arrangements and number of persons. To be able to seat comfortably, one person requires a table area of about 60cm wide and 40cm deep, and to provide sufficient clearance between individuals, one person requires a table area of 70cm wide and 65cm deep. The standard height of the table is 75cm [7].

Table Top

The dimension of the table top is given as

$$V = L \times b \times t \quad (61)$$

Where; V, L, b and t are the volume, length, breadth and thickness of the table top respectively.

Table Covers

The dimension of the table right-hand-side cover to is given as

$$V_1 = L_1 \times b_1 \times t_1 \quad (62)$$

Where, V_1 , L_1 , b_1 and t_1 are the volume, length, breadth and thickness of the right-hand-side cover respectively.

The dimension of the table left-hand-side cover to is given as

$$V_2 = L_2 \times b_2 \times t_1 \quad (63)$$

Where, V_2 , L_2 , b_2 and t_1 are the volume, length, breadth and thickness of the left-hand-side cover respectively.

The dimension of the table front cover to is given as

$$V_3 = L_3 \times b_3 \times t_1 \quad (64)$$

Where, V_3 , L_3 , b_3 and t_1 are the volume, length, breadth and thickness of the front cover respectively.

The dimension of the table back cover to is given as

$$V_4 = (L_4 \times b_4 - L' \times b') \times t_1 \quad (65)$$

Where, V_4 , L_4 , b_4 and t_1 are the volume, length, breadth and thickness of the back cover respectively.

Table Metal Frame

Square pipes were used for the design of the table metal frame

Total length of the frame top = perimeter of the frame top + length of cross member

$$L_{T1} = 2(L_5 + b_5) + L_6 \quad (66)$$

Total length of table stand,

$$L_{T2} = nL_7 \quad (67)$$

Where n and L_7 is the number and length of metal stand respectively.

There are three different auxiliary cross members with length L_8 , L_9 and L_{10} . Total length of auxiliary members is

$$L_{T3} = 2(L_8 + L_9 + L_{10}) \quad (68)$$

Total length of square pipes for the entire frame

$$L_T = L_{T1} + L_{T2} + L_{T3} \quad (69)$$

Design Calculation

In the evaporator design calculations, the values of 0.362W, 3.762W, 13.93W and 2.09W were obtained as rate of heat transfer through cabinet cover, Leakage load, Usage load and Supplementary load respectively for a single port. The rate of heat rejected by the condenser is 425.39W with a compressor rating of 69.3W for three participants. The overall table top area is $2.1 \times 0.65\text{m}^2$. The lagging materials for the design of the cooling table are Formica, Polystyrene, Marflet and Plywood.

Conclusion

A simple design of a multipurpose cooling table with locally sourced materials for conferencing. The purpose of the table is to allow conference participants to keep soft drinks or water chill. This table has benefit in the tropics where the ambient temperature can reach 40°C . The prototype for a 3 participant table requires about 70W compressor and provides and maintains cooling of drinks.

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