Theoretical Design of a Non-Cyclic Cooling System using Pykrete as a Cooling Material and Considering the System as a Heat Exchanger

Divyashree Deore[1], Sarthak Sharma[2]

B.E. Mechanical Engineering, Sinhgad Academy of Engineering, Pune, Maharashtra, India

Abstract: ***A non-cyclic cooling unit was theoretically designed with supply of air similar to that of commercially available A.C. unit producing one ton of refrigeration. The minimum temperature for the design was considered to be 16℃. The element used for cooling the air is Pykrete. The various stable temperatures of Pykrete were experimentally found. Also, the cooling capacity of designed unit was found theoretically. The working principle of this system is similar to that of Thermal Energy Storage system. The calculations were carried out considering this system would act as a heat exchanger.***

Keywords: Non-Cyclic Cooling System, Pykrete, Stable Surface temperatures, Thermal Energy Storage System, Heat Exchanger

1. Introduction

In this method Pykrete is used for keeping the space at temperature below the surrounding temperature. Pykrete is a frozen composite material made of approximately 14 percent sawdust or some other form of wood pulp (such as paper) and 86 percent ice by weight (6 to 1 by weight). The temperature of Pykrete is experimentally found to be 8°C, hence it is assumed that it can be used to maintain the temperatures of about 16°C. To use the Pykrete for cooling effect a closed and insulated chamber is required. Inside the chamber Pykrete is kept with Type L copper tubing runs through it. The Type L Copper tube dimensions have been taken from the Copper Tube Handbook, by Copper Development Association Inc. From one side of the tubing the atmospheric air enters the chamber and from the other side it is supplied to a space which is to be cooled. This method of cooling is similar to that of Thermal Energy Storage System being used for part cooling of utility spaces like offices, retail spaces, server rooms etc. It allows excess thermal energy to be collected for later use, hours, days or many months later, at individual building, multiuser building, district, town or even regional scale depending on the specific technology. As examples: energy demand can be balanced between day time and night time; summer heat from solar collectors can be stored inter-seasonally for use in winter; and cold obtained from winter air can be provided for summer air conditioning. Storage mediums include: water or ice-slush tanks ranging from small to massive, masses of native earth or bedrock accessed with heat exchangers in clusters of small-diameter boreholes (sometimes quite deep); deep aquifers contained between impermeable strata; shallow, lined pits filled with gravel and water and top-insulated; and eutectic, phase-change materials. Melting rate of Pykrete is considerably lower than that of Ice and the T.E.S. system based on Pykrete could run for a longer time before refreezing the cooling medium. It would also require less amount of energy to refreeze.

A proposed cooling system based on the following design is shown as follows –

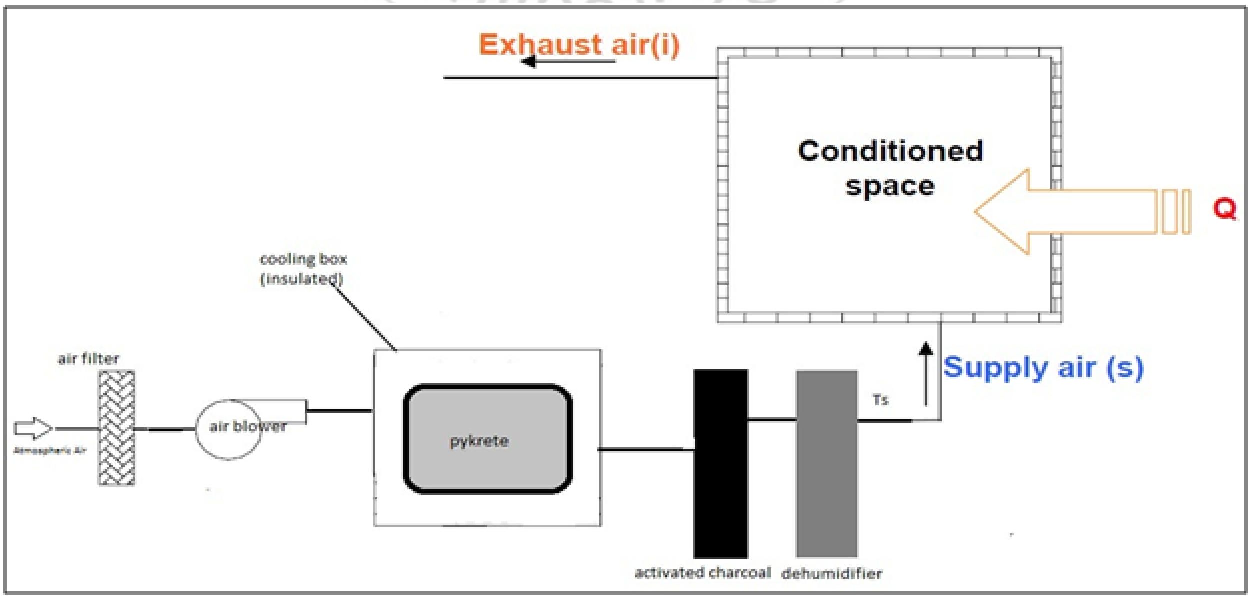

Figure 1

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2. Construction

The unit consists of a closed box insulated on all its faces. This box has copper tubing through it which would carry air from the atmosphere to the cooled space. The tubing material used is Type L copper tubes of nominal size 3/4 inch. The system also has an agitator provided so that in case the Pykrete melts completely, the sawdust in the Pykrete would not settle at the bottom of the box and its refreezing would be easier. The insulation thickness around the box is assumed to be 10 cm along all dimensions similar to that used in commercially available ice boxes. The insulating material used is same as that used in commercial ice boxes.

Schematic Diagram

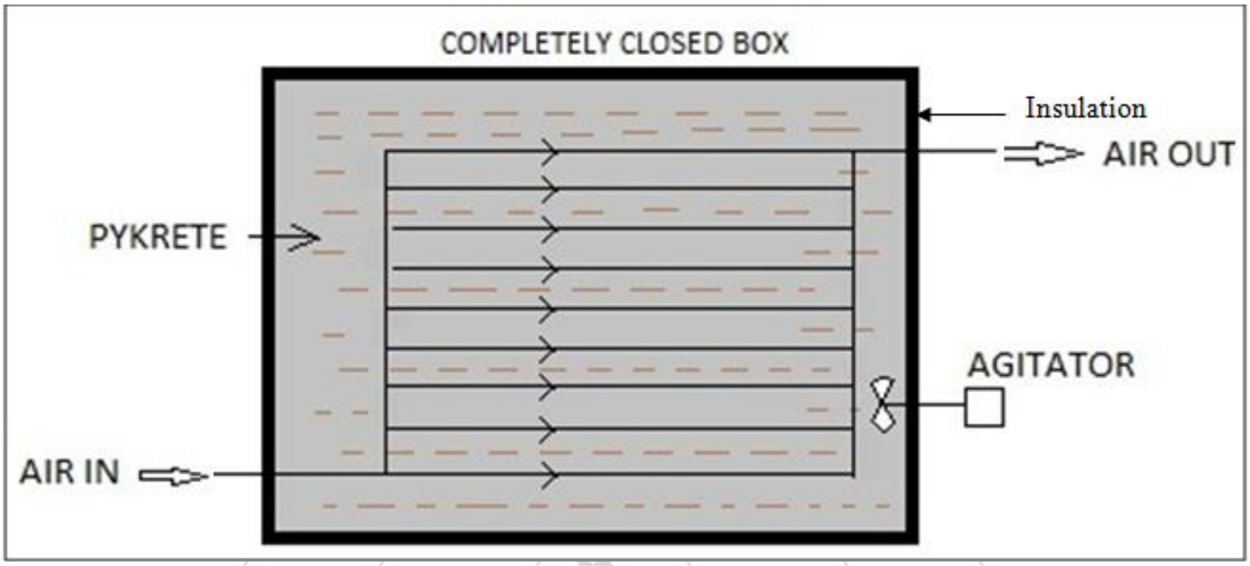

Figure 2

3. Experimental Observations

Stable surface temperature of Pykrete when insulated (Photograph 1) and when un-insulated (Photograph 2) –

Photograph 1

Photograph 2

For ease of calculations the temperature is taken as 8°C.
For ease of calculations the temperature is taken as 12°C

3.1 Calculations

Properties of Air at 32°C
Density = 1.572 $kg.m^{-3}$
Specific heat at constant pressure = 1.0065 $kJ.kg^{-1}.K^{-1}$
Dynamic viscosity = $1.8774*10^{-5}$ $kg.m^{-1}.s^{-1}$
Kinematic viscosity, ν = $1.6224*10^{-5}$ $m^2.s^{-1}$
Conductivity, k_{air} = 0.026489 $W.m^{-1}$ K^{-1}
Prandtl number = 0.71341
Thermal diffusivity = $2.274*10^{-5}$ $m^2.s^{-1}$
Thermal expansion co-efficient = $3.2771*10^{-3}$ K^{-1}
Dimensions of Type L Copper tubing of nominal size ¾ in are as follows –
Inner diameter, Di = 0.02 m

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Outer diameter, Do = 0.022225 m
Wall thickness = 0.01143 m
Velocity of Air, V = 2.5 m.s^{-1}

Reynold's number, $Re = V * \frac{Di}{\nu}$

Re = 3078.8177

Since, $1*10^4 < Re < 1*10^5$

Local convective heat transfer coefficient,

$$h = 0.023*\frac{kair}{Di}*(Re)^{0.8}*(Pr)^{1/3}$$

h = 16.811 W.m^{-1}K^{-1}

Since the working of this system is assumed to be similar to that of single pass heat exchangers, following are the calculations for it –

Case 1

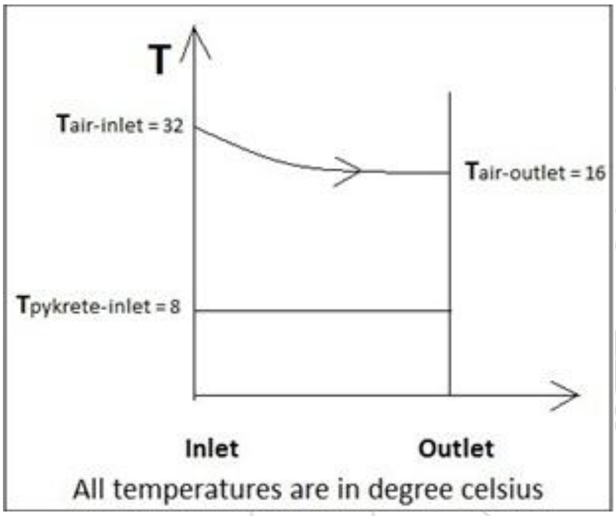

Figure 3

Θ_1 = (Inlet temperature of air – Stable surface temperature of Pykrete at Air Inlet)

Since the Pykrete is kept inside an insulated chamber the stable surface temperature of Pykrete is taken as 8°C

Temperature of Air at inlet is considered to be 32°C

Θ_1 = 32 – 8 = 24°C or 24K

Considering the air is cooled to 16°C (similar to that of commercially available A.C. unit)

Also, considering that the temperature of Pykrete will not increase noticeably.

Θ_2 = (Outlet temperature of air – Stable surface temperature of Pykrete at Air Outlet)

Θ_2 = 16 – 8 = 8°C or 8K

Now

Thermal conductivity of Copper, k_{Cu} = 385 W.m^{-1}.K^{-1}

Amount of heat absorbed from air can be given by,

$Q = U*A*\Theta_m$ ...**1**

Where,

U is overall heat transfer co-efficient

A is wetted area of copper tube

Θ_m is the Logarithmic Mean Temperature Difference (L.M.T.D.)

Now,

$$\Theta m = \frac{(\Theta 1 - \Theta 2)}{\ln\left(\frac{\Theta 1}{\Theta 2}\right)}$$

$$\Theta m = \frac{24-8}{\ln(\frac{24}{8})}$$

Θ_m = 14.564 K ...A

$$U = \frac{1}{\frac{Do}{Di*h}+\frac{Do}{Kcu}*\ln(\frac{Do}{Di})} = 15.1273 \text{ W.m}^{-2}.\text{K}^{-1} \text{ ...B}$$

A = Do * π * L = 0.069822 * L m^2 ...C

Where L is the length of tube required to achieve the above temperature difference

Substituting A, B, C in Equation 1,

Q = 15.1273 * 0.069822*L * 14.564

Q = 15.3828 * L W 2

Now the heat gained by Pykrete = the heat lost by Air

Assuming a cooling of 1 T.R. is achieved,

Therefore heat lost by Air is 1 T.R. i.e. Q = 3516 W.

Substituting this value in equation 2

3516 = 15.3828 * L

Therefore, L = 228.567 m ≈ 229 m. ...D

Case 2: Considering the system acts similar to Parallel Flow Heat Exchanger

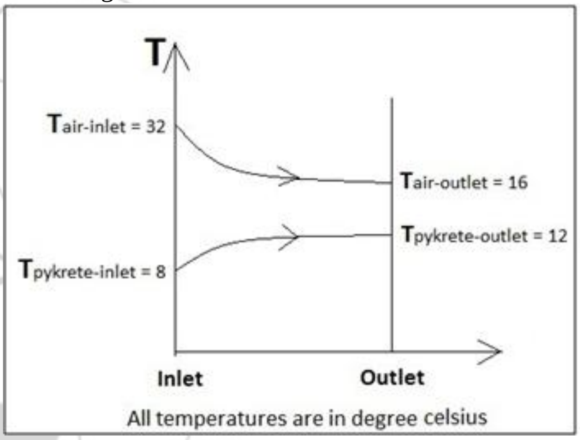

Figure 4

Θ_1 = (Inlet temperature of air – Stable surface temperature of Pykrete at Air Inlet)

Since the Pykrete is kept inside an insulated chamber the stable surface temperature of Pykrete is taken as 8°C

Temperature of Air at inlet is considered to be 32°C

Θ_1 = 32 – 8 = 24°C or 24K

Considering the air is cooled to 16°C (similar to that of commercially available A.C. unit)

Considering after a certain amount of time the Pykrete will act similar to a Pykrete block kept un-insulated, therefore, stable surface temperature of Pykrete will increase to 12°C

Θ_2 = (Outlet temperature of air – Stable surface temperature of Pykrete at Air Outlet)

Θ_2 = 16 – 12 = 4°C or 4K

$$\Theta m = \frac{(\Theta 1 - \Theta 2)}{\ln\left(\frac{\Theta 1}{\Theta 2}\right)}$$

$$\Theta m = \frac{(24-4)}{\ln\left(\frac{24}{4}\right)}$$

Θ_m = 11.162 K

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By performing calculations similar to Case 1, for parallel flow

L = 298.231 m ≈ 299 m ...E

Case 3: Considering system acts similar to Counter Flow Heat Exchanger

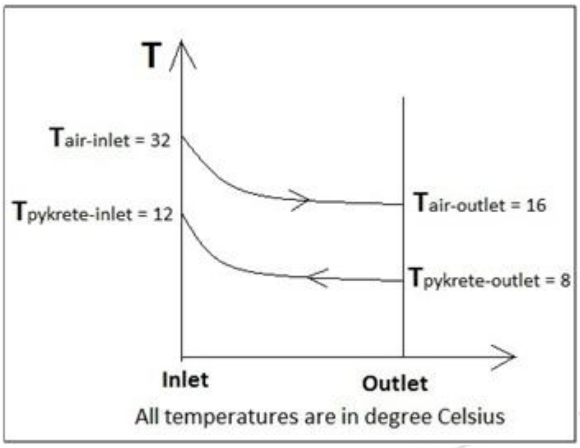

Figure 5

Θ_1 = (Inlet temperature of air – Stable surface temperature of Pykrete at Air Inlet)

Since the Pykrete is kept inside an insulated chamber the stable surface temperature of Pykrete is taken as 8℃

Temperature of Air at inlet is considered to be 32℃

$\Theta_1 = 32 - 12 = 20$℃ or 20K

For dimensions of Pykrete block,

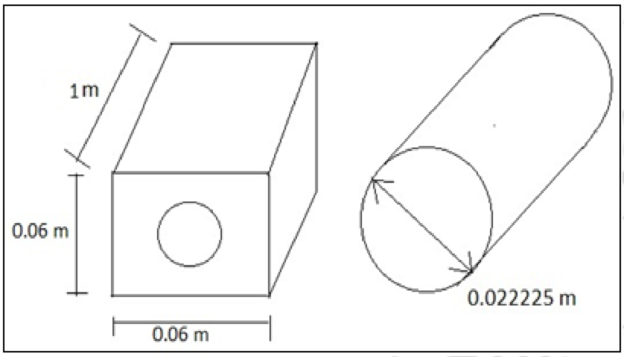

Figure 6

Assume the total length of Pykrete block is 1 m, therefore, for a total tube length of 299 m (consider 300 m for ease of calculations), Total number of tubes required = 300.

Assuming the tubes are arranged in a matrix of 15*20 tubes

Consider face width required for one tube = 6 cm

Cross-sectional area for Pykrete block for 1 tube = 36 cm^2

Total width of Pykrete block = 20*6 = 120 cm

Total height of Pykrete block = 15*6 = 90 cm

Therefore cross-sectional area of Pykrete block for 300 tubes = 10800 cm^2

Therefore, dimensions of the complete Pykrete block are 100 cm * 120 cm * 90 cm

For a cylinder of Outer diameter 2.2225 cm and length 100 cm

Volume of one tube = 387.948 cm^3

Volume for 300 such tubes = 116384.3741 cm^3

Total volume available = 100 * 120 * 90 = 1080000 cm^3

Considering the air is cooled to 16℃ (similar to that of commercially available A.C. unit)

Considering after a certain amount of time the Pykrete will act similar to a Pykrete block kept un-insulated, therefore, stable surface temperature of Pykrete will increase to 12℃

Θ_2 = (Outlet temperature of air – Stable surface temperature of Pykrete at Air Outlet)

$\Theta_2 = 16 - 8 = 8$℃ or 8K

$$\Theta m = \frac{(\Theta 1 - \Theta 2)}{\ln\left(\frac{\Theta 1}{\Theta 2}\right)}$$

$$\Theta m = \frac{(20 - 8)}{\ln\left(\frac{20}{8}\right)}$$

$\Theta_m = 13.0963$ K

By performing calculations similar to Case 1, for counter flow

L = 254.183 m ≈ 255 m. ...F

As seen in equations D, E and F the effective length L is maximum in Case 2, hence even if system acts as Case1 or Case3, similar effects could be produced by using the tubing length calculated in Case2.

Therefore, we take length of tubing as calculated in Case 2

Volume covered by Pykrete = Total volume available – Volume of 300 tubes = 963615.6259 cm^3

Now,

Mass of Pykrete used = density of Pykrete, $\rho_{Pykrete}$ * Volume covered by Pykrete

$\rho_{Pykrete} = 980$ kg/m^3

Mass of Pykrete used = 980 * 963615.6259 * 10^{-6}= 944.3433 kg

Check for calculations

Heat absorbed = Mass of Pykrete * Specific heat of Pykrete * Increase in temperature of Pykrete

Since only the frozen water in Pykrete will undergo phase change it will absorb the majority of heat given out by air as compared to sawdust. Therefore specific heat of Ice is taken into account for calculation instead of specific heat of Pykrete.

Specific heat of Ice = 2.05 * 10^3 $J.kg^{-1}.K^{-1}$

Therefore, the above equation becomes

3.516 = Mass of Pykrete * 2.05 * 10^3 * (12 – 8)

Mass of Pykrete = 4.3 * 10^{-4} kg

Since Mass of Pykrete used >> Mass of Pykrete required, the desired temperatures could be achieved.

4. Results

Overall dimensions = 100 cm * 120 cm * 90 cm

Mass of Pykrete used = 944.3433 kg

Total number of tubes = 300

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5. Applications

1. Centralised Cooling of Public Spaces

Instead of using a bulky water chilling AHU, a Pykrete based T.E.S. can be used reducing the overall size of the centralised A.C. unit

2**. Cooling Purposes for Large Server System**

Large server rooms generate a sizeable amount of heat since a number of computer systems are used. Hence, they require to be maintained at a certain temperature. This can be achieved by using a T.E.S system which consumes less power than V.C.C. based system.

3. Cooling Of Controlled Environment (C.A. / M.A.)

For food preservation and storage of biomedical and biochemical matter requires precisely controlled atmosphere and maintenance of such conditions. In short, such materials are required to be stored in C.A./M.A. systems. Since, rate of heat addition to Pykrete is very slow, it can maintain a particular temperature for a prolonged period of time even during power outages.

6. Conclusion

From the above calculations, it has been found out that, cooling capacity of 1 T.R., a Pykrete block of 100*120*90 cc is required. Cooling capacity according to requirement can be varied from this value of cooling capacity by varying the volumetric flow rate of air through the system. Hence the desired temperature can be achieved.

Appendix:

1. For type L Copper tubing, Nominal size used i.e. ¾ in.
   1.1. Outer diameter = 0.875 in.
   1.2. Inner diameter = 0.785 in.
   1.3. Wall thickness = 0.45 in.
   1.4. Length of tubing used = 30 cm.
2. Properties of Air at 32^0
   2.1. Density = 1.572 $kg.m^{-3}$
   2.2. Specific heat at constant pressure = 1.0065 $kJ.kg^{-1}.K^{-1}$
   2.3. Dynamic viscosity = $1.8774*10^{-5}$ $kg.m^{-1}.s^{-1}$
   2.4. Kinematic viscosity = $1.6224*10^{-5}$ $m^2.s^{-1}$
   2.5. Conductivity = 0.026489 $W.m^{-1}.K^{-1}$
   2.6. Prandtl number = 0.71341
   2.7. Thermal diffusivity = $2.274*10^{-5}$ $m^2.s^{-1}$
   2.8. Thermal expansion co-efficient = $3.2771*10^{-3}$ K^{-1}
3. Specific heat of Ice = 2.05 $kJ.kg^{-1}.K^{-1}$
4. Volume flow rate of supply air = 630 Cmpm
5. Flow velocity of supply air = 150 mpm
6. Mechanical properties of Ice and Pykrete

Table 1

Mechanical Property	Ice	Pykrete
Melting Point (℃)	0	9
Steady State Temperature (℃)	-0.3 to 0	12
Steady state temp. Under controlled environment (℃)	-3 to 0	8
Density (kgm^{-3})	910	980`
Thermal Conductivity ($W.m^{-1}.K^{-1}$)	2.18	0.48

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Author Profile

Divyashree Deore, B.E. Mechanical Engineering, Sinhgad Academy of Engineering, Pune

Sarthak Sharma, B.E. Mechanical Engineering, Sinhgad Academy of Engineering, Pune

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