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Thermal Engineering

Elixir Thermal Engg. 107 (2017) 46835-46839

ISSN: 2229-712X

Two Stage Evaporative Cooling Based Air Refrigeration System for very low Temperatures (Cryogenics)

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ARTICLE INFO

Article history:
Received: 26 April 2017;
Received in revised form: 21 May 2017;
Accepted: 30 May 2017;

Keywords
Evaporative Cooling
Indirect Cooling,
Intercoolers & Aftercoolers,
Eco-friendly,
Cryogenics.

ABSTRACT

Development of eco-friendly systems and energy efficient systems has been a great concern for sustainable development. In the present research paper, we are using a two-stage evaporative cooler (TSEC) consisting of two evaporative cooling chambers. The temperature drop through TSIEC can be achieved to be about 100K or below by applying the combined concept of bootstrap air refrigeration cycle and evaporative air refrigeration cycle. In this system we are using indirect evaporative cooling of compressed air in two stages of compression followed by cooling to attain very low temperature which can be used for scientific researches and cryogenics.

Introduction

A cryogenic experiment or system is normally dominated by the need to get something cold and keep it cold, with other elements of the design subservient to that. Generally, the need to operate at cryogenic temperatures makes even an otherwise simple experiment complicated, and the colder you need to go, the harder life generally gets. Since it is so time consuming to get things cold, the ability to experiment with new techniques is somewhat limited, and most low temperature labs cling to a set of tried-and-trusted methods (Cascade Systems). Often these differ from lab to lab, and in the most interesting cases are contradictory. In present scenario, development of eco-friendly systems and energy efficient systems has been a great concern for sustainable development. Evaporative cooling is a very effective and efficient way to attain low temperature. By using air compressor in place of fan or blower, the final temperature of air can be reduced to a great extent. The cold compressed air when freed to expand to atmospheric pressure attains a very low temperature giving high degree of cooling. The use of evaporative cooling has a great scope in maintaining low temperature. In the present research paper, we are using a two-stage evaporative cooler (TSEC) consisting of two evaporative cooling chambers. The temperature drop through TSEC can be achieved to be about 100K or below by applying the combined concept of bootstrap air refrigeration cycle and evaporative air refrigeration cycle. In this system we are using indirect evaporative cooling of compressed air in two stages of compression followed by cooling to attain very low temperature which can be used for scientific researches and cryogenics. There are a number of benefits of using a two stage evaporative cooling based air refrigeration system over the conventional cascade system such as eco-friendly process, higher COP and gain of very low temperature in a single cycle.

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Theory of evaporative cooling

Evaporative cooling is a process of heat and mass transfer based on the transformation of sensible heat into latent heat. The non-saturated air reduces its temperature, providing the sensible heat that transforms into latent heat to evaporate the water. If the process develops in ideal adiabatic conditions, the dry bulb air temperature decreases as this transformation develops, increasing its humidity. This heat exchange continues until the air reaches its saturated state, when the air and water temperature reach the same value, called "adiabatic saturation temperature", being the process known as "adiabatic saturation". To define this temperature we can suppose a long adiabatic tunnel, in which the humid air is introduced in certain conditions, while water is sprayed inside the tunnel and then re-circulated, in such a way that the air becomes saturated (see Figure 1).

The adiabatic saturation temperature, T_{sat}, is the temperature that the air reaches when gets to the output of the tunnel, if water is provided and evaporated at that temperature.

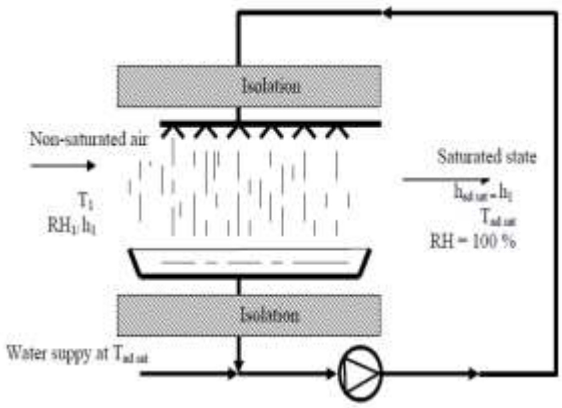

Figure1. Basic of Evaporative cooling.

Direct evaporative cooling systems

In direct evaporative cooling, the conditioned air comes in direct contact with the wetted surface, and gets cooled and humidified. Figure 2 shows the schematic of a direct, evaporative cooling system and also the process on psychometric chart. As shown in the figure, hot and dry outdoor air is brought in contact with the wetted surface or spray of water droplets in the air washer. The air gets cooled and humidified due to simultaneous transfer of sensible and latent heats between air and water (**process o-s**). The cooled and humidified air is supplied to the conditioned space, where it extracts the sensible and latent heat from the conditioned space (**process s-i**). One can define the efficiency or effectiveness of the evaporative cooling system ε as:

$$\varepsilon = (t_o - t_s)/(t_o - t_{o,wbt})$$

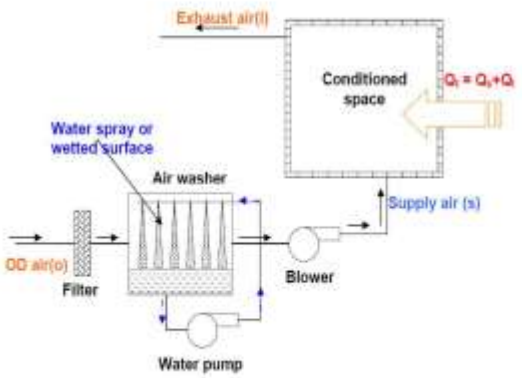

Figure 2.Schematic diagram of direct contact evaporative cooling.

The amount of supply air required $\dot{m}_s$ can be obtained by writing energy balance equation for the conditioned space, i.e.

$$\dot{m}_s = Q_t/(h_i - h_s)$$

where Q_t is the total heat transfer rate (sensible + latent) to the building, h_i and h_s are the specific enthalpies of return air and supply air, respectively.

Indirect evaporative cooling system

In an indirect evaporative cooling process, two streams of air - primary and secondary are used. The primary air stream becomes cooled and humidified by coming in direct contact with the wetted surface (o-o'), while the secondary stream which is used as supply air to the conditioned space, decreases its temperature by exchanging only sensible heat with the cooled and humidified air stream (o-s). Thus the moisture content of the supply air remains constant in an indirect evaporative cooling system, while its temperature drops. Since the moisture content of supply air remains constant in an indirect evaporation process, this provides greater degree of comfort in regions with higher humidity ratio. The commercially available indirect evaporative coolers have saturation efficiency as high as 80%.

Multi-stage evaporative cooling systems

One simple improvement is to sensibly cool the outdoor air before sending it to the evaporative cooler by exchanging heat with the exhaust air from the conditioned space. It is also possible to mix outdoor and return air in some proportion so that the temperature at the inlet to the evaporative cooler can be reduced, thereby improving the performance. Several other schemes of increasing complexity have been suggested to get the maximum possible benefit from the evaporative cooling systems.

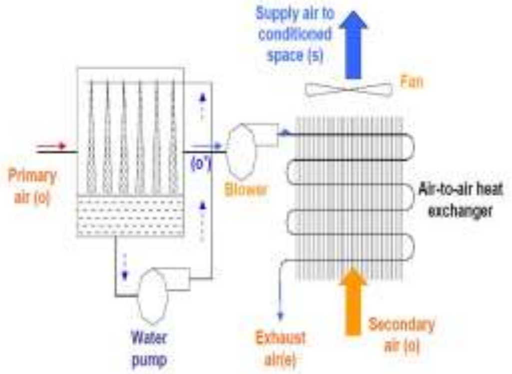

Figure 3.Schematic diagram of indirect contact evaporative cooling.

Figure 4 shows a typical two-stage evaporative cooling system and the process on a psychometric chart. As shown in the figure, in the first stage the primary air is cooled and humidified (o -o') due to direct contact with a wet surface cools the secondary air sensibly (o -1) in a heat exchanger. In the second stage, the secondary air stream is further cooled by a direct evaporation process (1-2). Thus in an ideal case, the final exit temperature of the supply air (t_2) is several degrees lower than the wet bulb temperature of the inlet air to the system ($t_{o'}$).

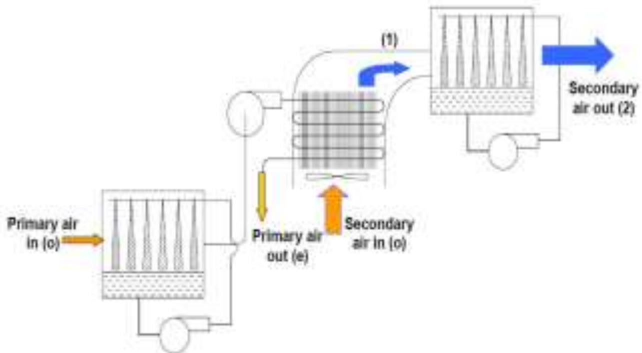

Figure 4 Schematic diagram of two stage evaporative cooling.

Two stage indirect evaporative cooling System

Two-stage indirect evaporative cooler (TSIEC) consists of two heat exchanger and two evaporative cooling chambers. The performance of cooler has been evaluated in terms of temperature drop, efficiency of the evaporative cooling and effectiveness of TSIEC over single evaporation.. With the use of indirect evaporative cooling in air refrigeration cycles, it is possible to achieve very low temperatures for the use in cryogenics.

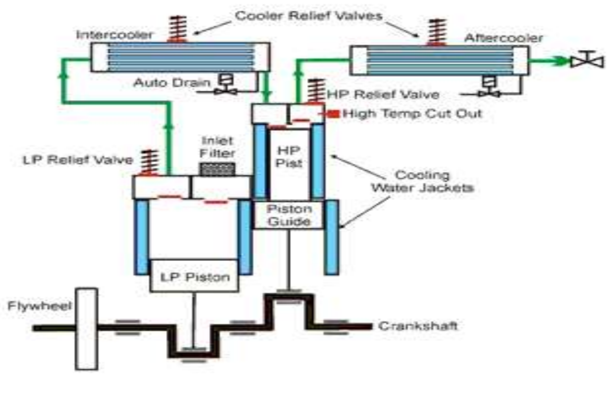

Figure 5. Two stage indirect evaporative cooling system.

By following two stage evaporative cooling the cooling effect and hence the COP of the system can be increased drastically. This system is less power consuming, simple in construction, fully eco-friendly and provides a higher refrigeration effect. No refrigerant is required in this system as air itself works as refrigerant.

Basic Assumptions of Numerical Analysis

A. The atmospheric air is dry.
B. The first stage of compression behaves as an isothermal compression, i.e. it is a case of perfect inter-cooling.
C. The specific heat ratio is equal to 1.4(γ = 1.4)
D. All the compression processes are isentropic.
E. The average wet bulb temperature is about 17°C.
F. The compressed air is cooled to 20°C using evaporative cooling.
G. The room temperature is taken to be around 30°C.
H. Take Gas Constant R = 0.287KJ/kg K.
I. Take Specific heat at constant pressure as 1 KJ/Kg

Mathematical Analysis

For a compression ratio of 5.

Final attained temperature of the air in the evaporator is calculated as

$$\frac{T_{final}}{T_c} = \left(\frac{p_{final}}{p_c}\right)^{\frac{\gamma-1}{\gamma}}$$

Putting T_c = Temperature of air after evaporative cooling = 20°C = 293 K

$\frac{p_c}{p_{final}}$ = 5 and γ = 1.4, we get

$$T_{final} = \frac{293}{5^{.2857}}$$

= 185 K

Hence the refrigeration effect per unit mass flow rate of air will be

$C_p(T_{room} - T_{final})$
= 1x(303-185)
= 118KJ/kg of air

Work done per unit mass of air can be calculated as

$$\frac{2\gamma}{\gamma-1}R \quad T_{room}\left[\left(\frac{p_c}{p_{final}}\right)^{\frac{\gamma-1}{2\gamma}} - 1\right]$$

Putting relative values, we get,

$$\frac{2x1.4}{1.4-1}x.287x \quad 303\left[\left(\frac{5}{1}\right)^{\frac{1.4-1}{2x1.4}} - 1\right]$$

=157.355KJ/kg of air

Hence COP of the overall system,

$$= \frac{\text{Refrigeration Effect}}{\text{Work done}}$$

$$= \frac{118}{157}$$

=0.7516

Similarly, by calculating the above parameters for different compression ratio following results (Table 1) can be obtained.

Control over Cooling Loads

The two stage evaporative cooling based air refrigeration cycle can meet the variable load requirements just by adjusting the mass flow rate of air. It is clear from the above analysis that the two stage evaporative cooling based air refrigeration system is beneficial for smaller loads and its COP decreases with the increase in compression ratio. Thus for a cooling load capacity of 1TR, the mass flow rate of required air will be

$$m_a = \frac{210Q}{c_p x (T_{room} - T_{final})}$$

= 1.775Kg/min (for a compression ratio 5)
=1.385Kg/min (for a compression ratio 10)
=1.25Kg/min (for a compression ratio 15)

Hence, by controlling the mass flow rate of air required the cooling load of the refrigeration cycle can be varied.

Results and Discussion

The study and numerical analysis clearly shows that Two Stage Evaporative cooling based air refrigeration system can be efficiently used for getting lower temperatures with wide range of output temperature. The system is more efficient at lower compression ratio but it can be used in places where lower temperature matters more than the power consumption such as cryogenics.

Variation of output temperature of two stage evaporative cooling based air refrigeration system (TSECARS) with respect to the compression ratio of compressor can be plotted as under:

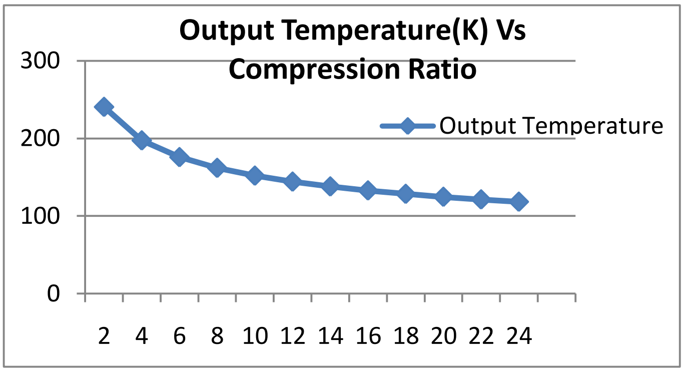

Fig 6. Variation of final temperature gain with respect to cooling load of evaporative cooling based air refrigeration cycle.

The above graph clearly shows that the output temperature of the air can be reduced to about 100K by selecting proper compression ratio.

Table 1. Outputs of TSIECARS at various compression ratio.

S. No.	Compression Ratio (r)	Final Temp. (T_1 in K)	Refrigeration Effect (R)	Work Done (W)	COP
1.	2	240.36	62.64	63.33	0.99
2.	4	197.18	105.80	133.49	0.79
3.	5	185.00	118.00	157.35	0.75
4.	6	175.61	127.39	177.49	0.72
5.	8	161.75	141.25	210.46	0.67
6.	10	151.76	151.24	236.98	0.64
7.	12	144.06	158.94	259.29	0.61
8.	14	137.85	161.15	278.61	0.59
9.	15	135.16	167.84	287.53	0.58
10.	16	132.69	170.31	298.69	0.57
11.	18	128.30	174.70	311.04	0.56
12.	20	124.50	178.50	324.98	0.55
13.	22	121.15	181.85	337.77	0.54
14.	24	118.18	184.82	349.60	0.53
15.	25	116.81	186.19	355.20	0.52

It can be used in wide range of output temperature by just adjusting the compression ratio.

Variation of refrigeration effect of two stage evaporative cooling based air refrigeration system (TSECARS) with respect to the compression ratio of compressor can be plotted as under:

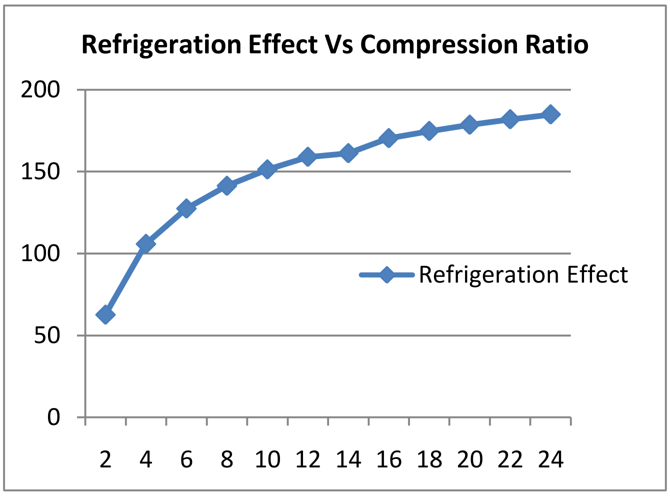

Fig 7. Variation of refrigeration effect of the cycle with respect to compression ratio.

The above graph clearly shows that the refrigeration effect of two stage indirect evaporative cooling based air refrigeration system can be varied by selecting proper compression ratio. The refrigeration effect of the cycle increases with the increase in the compression ratio. The above refrigeration effect is calculated per unit mass flow rate of the refrigerating air. By adjusting the mass flow rate of the compressed air the refrigeration effect of the cycle can be calculated.

Variation of COP of two stage evaporative cooling based air refrigeration system (TSECARS) with respect to the compression ratio of compressor can be plotted as under:

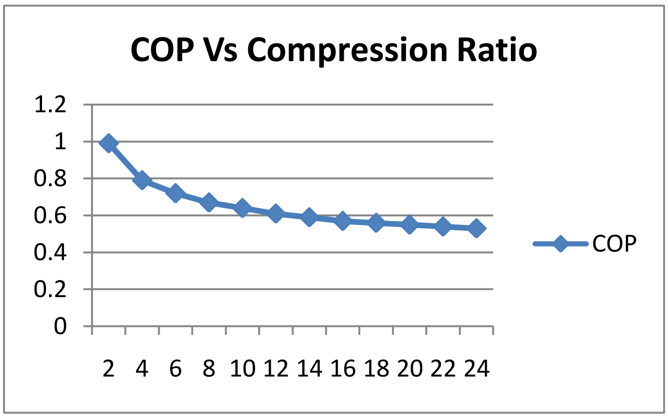

Fig 8. Variation of COP with respect to compression ratio.

The above graph clearly shows that the COP of two stage indirect evaporative cooling based air refrigeration system encounters more losses with the increase in compression ratio. The COP of the cycle decreases with the increase in the compression ratio.

The relative gain or loss of evaporative cooling based air refrigeration cycle over the conventional Air Refrigeration System can be summarized as follows:

The above graph clearly shows that the COP of two stage indirect evaporative cooling based air refrigeration system encounters more losses with the increase in compression ratio. The COP of the cycle decreases with the increase in the compression ratio.

The relative gain or loss of evaporative cooling based air refrigeration cycle over the conventional Air Refrigeration System can be summarized as follows:

S. No	Particular	Normal Air Refrigeration System	Evaporative Air Refrigeration System
1.	Attaining of low temperature	Up to 170K	Up to 100K
2.	Overall COP of the System	Less than .5	More than .5
3.	Power Consumption	High	Less
4.	Amount of air circulated required	High	Low
5.	Design Considerations	Simple	Simple
6.	Initial Cost	Low	High

Advantages of using double stage evaporative cooling based air refrigeration system

- Its initial construction cost is very less.
- It consumes less power as compared to conventional air conditioning.
- It does not use any chemical refrigerant for the cooling purpose.
- It is fully eco-friendly and brings no hazards to the surroundings.
- It can be installed anywhere in an open place, even on roof tops.
- It has high cooling capacity.

Limitations of using double stage evaporative cooling based air refrigeration system

- The water needs to be refilled in the tank as it gets depleted with time.
- Its maintenance cost is high as its water pad needs to be changed each year.
- It needs to be cleaned regularly as biological growth may occur in water when used over a long period of time.
- It causes high vibration as reciprocating compressors are used.
- It requires large space area as compared to cascade systems.
- The air should be 100% free from moisture which requires additional units for removal of moistures.

Conclusion

The double stage evaporative cooling based air refrigeration system is a very efficient technique for producing very low temperature. With proper care it can easily meet the requirements of Vapour Compression Refrigeration system having a higher potential over conventional systems. The numerical analysis shows that it is very efficient in saving energy as well as in cooling effect. It is the most suitable method for gaining very low temperature for experimental analysis which require very low temperatures but with smaller cooling loads.

Future Scope

- The water filling system can be automated by connecting it with main supply and using proper sensors.
- The conventional water pads can be replaced with non degradable pads which do not require to be changed each year.
- By applying changes, it can prove to be the most efficient air refrigeration technique for cryogenics.
- It can be manufactured in any size to meet variable requirements of industries.
- The above cycle can also be used for air conditioning system.

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