Thermodynamic Analysis of Inlet Air Cooling System for a Centrifugal Compressor

Abhilash Suryan, Pradeep Arjunan, Gyu Wan Kim, and Heuy Dong Kim

1 Introduction

Efficient use of energy is regarded as a national benefit because it can reduce the level of energy imports from other countries and may slow down the rate at which domestic energy resources are depleted. Reducing energy use may be financially beneficial to the consumers if the energy savings offset any additional costs of implementing an energy-efficient technology. Exergy analysis is widely used to determine the energy efficiency of an industrial system. Exergy efficiency is more rational than energy efficiency; and exergy analysis is more helpful than energy analysis for locating and evaluating available energy-saving potentials, identifying opportunities for improvements in system design, and establishing cost-effective system maintenance programs.

Evaporative cooling systems take advantage of the fact that water has the highest value for the latent heat of vaporization of all known substances. Latent heat is defined as the amount of heat that is required to evaporate a liquid. In evaporative cooling this heat comes from the liquid itself, surrounding gas and the walls of the duct. Whenever dry air passes over water, some water will be absorbed by air because the temperature and vapor pressure of water and air attempt to equalize.

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Liquid water molecules become water vapor in dry air, through a process that uses energy to change the physical state. Heat energy is transferred from higher-temperature air to lower-temperature water, and thus air is cooled. Eventually, the air becomes saturated and unable to hold more water, and evaporation ceases. Limiting temperature attainable by evaporative cooling is the wet bulb temperature (WBT) corresponding to given initial conditions of air. Greater the difference between dry bulb and wet bulb temperatures, the greater will be the evaporative cooling potential. When temperatures are the same, no net evaporation of water in air is possible, and there will not be any cooling effect.

Inlet fogging is an environmentally friendly evaporative cooling technique characterized by lower costs and ease of maintenance. In inlet fogging systems, required quantity of water is injected into air flow in the form of fine sprays from fog nozzles at duct inlet. A number of sprays required to be deployed depend on initial conditions of air, air flow rate, and operating conditions of spray nozzles. Each spray consists of very tiny spherical droplets of various diameters (5–50 μm). Water droplets quickly take up the velocity of air flow within a few millimeters from the inlet. Droplets remain airborne for longer durations due to Brownian movement, and random collision with air molecules further slows down the droplet descent. Tiny water droplets contained in the spray create a large evaporative surface area and get evaporated by absorbing latent heat of vaporization from the surrounding air. Droplets undergo a reduction in size as they move toward the exit, cooling the surrounding air in the process and making it denser (Meher-Homji and Mee 1999, 2000a, b).

Inlet fogging has been in use for increasing the efficiency of gas turbine power plants. Chaker and Meher-Homji (2002) and Chaker et al. (2002a, b) have conducted elaborate studies on inlet fogging systems for gas turbine power plants. The same method has been attempted for inlet air cooling of a turbocompressor by Suryan et al. (2010a, b, 2011a, b).

Dincer and Rosen (2007) define exergy as a thermodynamic property that depends on both the state of the substance being considered and the state of the environment. Exergy is always evaluated with respect to a reference environment, i.e., dead state, and it is destroyed when irreversibility occurs. If an exergy analysis is performed on a system, thermodynamic imperfections can be quantified as exergy destruction, which represent losses in energy quality or usefulness. When a thermodynamic system is in equilibrium with the environment, the state of the system is referred as "dead state," and temperature of this state situation is called "dead state temperature" or reference temperature.

Many researchers had proposed novel methods and conducted studies on evaporative cooling methods and related technologies. Ren et al. (2001) conducted analysis of exergy of moist air and energy-saving potential in HVAC by evaporative cooling. Qureshi and Zubair (2003) applied exergy analysis to various psychrometric processes. Haseli et al. (2008) proposed a unified approach to exergy efficiency, environmental impact, and sustainable development for standard thermodynamic cycles. Hepbasli (2008) reviewed the exergetic analysis and assessment of renewable energy resources for a sustainable future. More recently, Caliskan et al. (2011a, b, 2012) had conducted a thermodynamic analysis on a novel air cooler used in buildings. In the present study, the method employed by Caliskan et al. is applied for the thermodynamic analysis of the inlet air cooling of a turbocompressor.

Nomenclature

c_p	Specific heat at constant pressure (Jkg^{-1}K^{-1})
ex	Specific exergy rate (kWkg^{-1})
Ex	Exergy rate (kW)
h	Specific enthalpy (Jkg^{-1})
m_a	Mass flow rate of air (kgs^{-1})
m_w	Mass flow rate of water (kgs^{-1})
p	Pressure (Nm^{-2})
Q	Heat transfer rate (kW)
R	Real gas constant (Jkg^{-1} K^{-1})
SI	Sustainability index
T	Temperature (K)
V	Specific volume (m^3 kg^{-1})
Greek letters	
ϕ	Relative humidity (%)
ψ	Exergy efficiency (%)
ω	Humidity ratio (kg$_w$/kg$_{da}$)
$\overline{\omega}$	Mole fraction ratio
Subscripts	
a	Air
C	Cooling
dest	Destruction
f	Fluid
g	Gas
in	Inlet conditions
l	Loss
o	Dead state
out	Outlet conditions
sat	Saturation
v	Vapor
w	Water

2 System Description

Inlet fogging system for a turbo air compressor used in the study is described in Fig. 1. The feasibility study was conducted on an installation supplying compressed dry air for the fabrication and assembly of electronic components. A large number of compressors are operated simultaneously for 24 h to meet the supply demands.

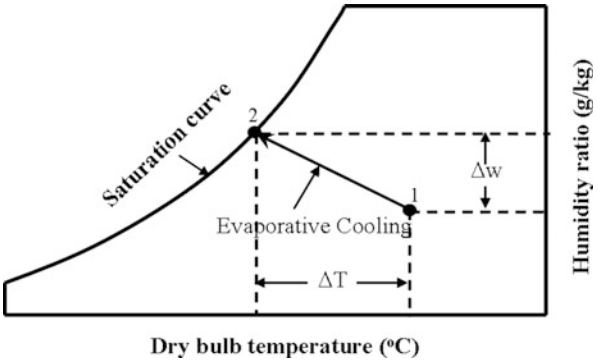


Fig. 1 Principle of evaporative cooling

The present study was conducted on a 9 MW turbocompressor with a rated air flow of 9000 m^3/h and pressure ratio of 8. However, measured air flow rate was 10–20% less than the rated flow depending on ambient conditions. Experimental studies made use of impaction pin nozzles and two-fluid nozzles. Measured quantity of water is sprayed through the nozzle array into the air stream in the form of fog. Fog droplets evaporate in the air duct, thereby cooling the inlet air. The parameters are determined by the instrumentation associated with the experimental setup. Ambient temperature and relative humidity are indicated on the weather station. Since the power savings are a strong function of the ambient weather conditions, detailed climatic study was also conducted (Suryan et al. 2008) to evaluate the evaporative cooling potential at the location of the turbocompressor installation (Fig. 2).

In order to assess possible damage to compressor blades due to droplet impingement and decide the sizing of the ducts, Suryan et al. (2010a, b, 2011a, b) had also conducted numerical and experimental studies on droplet travel and evaporation in the intake ducts of the turbocompressor. A thermodynamic analysis is done on the experimental inlet air cooling system in the present study. The data from some of the previous experimental studies of the authors are used in the present analysis.

3 Computational Method

Computational method of Caliskan et al. (2011a, b, 2012) is used in the present study. The exergy balance for the control volume around the experimental setup described in Fig. 1 may be written as follows:

$$\mathrm{Ex_{in}} = \mathrm{Ex_{out}} + \mathrm{Ex_{loss}} - \mathrm{Ex_{dest}} \tag{1}$$

where $\mathrm{Ex_{in}}$, $\mathrm{Ex_{out}}$, $\mathrm{Ex_{loss}}$, and $\mathrm{Ex_{dest}}$ are the exergy input, exergy output, exergy loss, and exergy destruction rates of the system, respectively:

$$\mathrm{Ex_{in}} = \mathrm{Ex_{in,a}} + \mathrm{Ex_{in,w}} \tag{2}$$

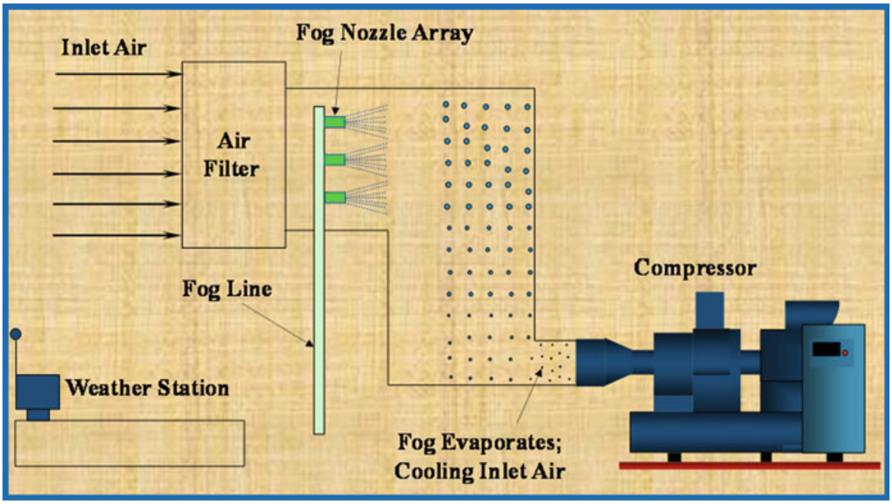


Fig. 2 Inlet fogging of turbocompressor

$$\mathrm{Ex}_{\mathrm{out}} = \mathrm{Ex}_{\mathrm{out,a}} \tag{3}$$

where $\mathrm{Ex}_{\mathrm{in,\ a}}$, $\mathrm{Ex}_{\mathrm{in,\ w}}$, and $\mathrm{Ex}_{\mathrm{out,\ a}}$ are the exergy input rate of inlet air, exergy input rate of water, and exergy rate of outgoing air, respectively.

The exergy input rate of dry air is calculated as

$$\mathrm{Ex}_{\mathrm{in,a}} = m_{\mathrm{a,in}}\,\mathrm{ex}_{\mathrm{in,a}} \tag{4}$$

where $m_{\mathrm{a,\ in}}$ is the mass flow rate of inlet air (kg/s) and $\mathrm{ex}_{\mathrm{in,\ a}}$ is the specific exergy flow of inlet air (kJ/kg) given by Shukuya and Hammache (2002) as

$$\begin{aligned}\mathrm{ex}_{\mathrm{in,a}} &= \left(c_{\mathrm{p,a}} + \omega c_{\mathrm{p,v}}\right) T_{\mathrm{o}}\left[\frac{T_{\mathrm{in}}}{T_{\mathrm{o}}} - 1 - \ln\left(\frac{T_{\mathrm{in}}}{T_{\mathrm{o}}}\right)\right] \\ &\quad + R_{\mathrm{a}} T_{\mathrm{o}} \ln\left[(1+\varpi)\ln\left(\frac{1+\varpi_{\mathrm{o}}}{1+\varpi}\right) + \varpi \ln\left(\frac{\varpi}{\varpi_{\mathrm{o}}}\right)\right] \\ &\quad + (1+\varpi) R_{\mathrm{a}} T_{\mathrm{o}} \ln\left(\frac{p_{\mathrm{in}}}{p_{\mathrm{o}}}\right)\end{aligned} \tag{5}$$

where $c_{\mathrm{p,\ a}}$ is the specific heat capacity of inlet air, $c_{\mathrm{p,\ v}}$ is the specific heat capacity of water vapor, To is the dead state temperature, T_{in} is the supply inlet dry bulb temperature, R_{a} is the specific ideal gas constant of inlet air, p_{in} is the supply inlet pressure, p_{o} is the dead state pressure, ω is the specific humidity of the inlet air, ϖ is the mole fraction ratio of the inlet condition, and $\varpi_{\mathrm{o}}$is the mole fraction ratio of the dead state condition.

The exergy input rate of water is obtained as

$$\mathrm{Ex}_{\mathrm{in,w}} = m_{\mathrm{w}}\mathrm{ex}_{\mathrm{w}} = m_{\mathrm{a}}\omega\,\mathrm{ex}_{\mathrm{w}} \tag{6}$$

where m_{w} is the mass flow rate of water ($\mathrm{kg_w/s}$) and $\mathrm{ex_w}$ is the specific exergy flow of water ($\mathrm{kJ/kg_w}$) given by the following equation:

$$\begin{aligned}\mathrm{ex_w} &= \left(h_{\mathrm{f}-T_{\mathrm{in}}} - h_{\mathrm{g}-T_{\mathrm{o}}}\right) - T_{\mathrm{o}}\left(s_{\mathrm{f}-T_{\mathrm{in}}} - s_{\mathrm{g}-T_{\mathrm{o}}}\right) \\ &\quad + \left(p_{\mathrm{in}} - p_{\mathrm{sat}-T_{\mathrm{in}}}\right)v_{\mathrm{f}-T_{\mathrm{in}}} - R_{\mathrm{v}}T_{\mathrm{o}}\ln\left(\phi_{\mathrm{o}}\right)\end{aligned} \tag{7}$$

where $h_{\mathrm{f}-T_{\mathrm{in}}}$ is the enthalpy of saturated water at inlet air temperature, T_{in}; $h_{\mathrm{g}-T_0}$ is the enthalpy (gas) of saturated water vapor at dead state temperature, T_{o}; $s_{\mathrm{f}-T_{\mathrm{in}}}$ is the entropy (fluid) of saturated water at inlet air temperature, T_{in}; $s_{\mathrm{g}-T_0}$ is the entropy (gas) of saturated water vapor at dead state temperature, T_{o}; p_{in} is the supply inlet pressure; $p_{\mathrm{sat}-T_{\mathrm{in}}}$ is the saturated water pressure at inlet air temperature, T_{in}; $v_{\mathrm{f}-T_{\mathrm{in}}}$ is the specific volume rate of the saturated water (fluid) at inlet air temperature, T_{in}; and R_{v} is the specific ideal gas constant of water vapor.

Exergy output rate $\mathrm{Ex_{out}}$ is equal to exergy rate of humid air $\mathrm{Ex_{ha}}$ and is obtained as follows:

$$\mathrm{Ex_{out,a}} = m_{\mathrm{a,out}}\,\mathrm{ex_{out,a}} \tag{8}$$

where $m_{\mathrm{a,\,out}}$ is the mass flow rate of outgoing air (kg/s), $\mathrm{ex_{out,\,a}}$ the specific exergy flow of outgoing air ($\mathrm{kJ/kg_w}$) which is given by Eq. 9:

$$\begin{aligned}\mathrm{ex_{out,a}} &= \left(c_{\mathrm{p,a}} + \omega c_{\mathrm{p,v}}\right) T_{\mathrm{o}}\left[\frac{T_{\mathrm{out}}}{T_{\mathrm{o}}} - 1 - \ln\left(\frac{T_{\mathrm{out}}}{T_{\mathrm{o}}}\right)\right] \\ &\quad + R_{\mathrm{a}}T_{\mathrm{o}}\ln\left[(1+\varpi)\ln\left(\frac{1+\varpi_{\mathrm{o}}}{1+\varpi}\right) + \varpi\ln\left(\frac{\varpi}{\varpi_{\mathrm{o}}}\right)\right] \\ &\quad + (1+\varpi)\,R_{\mathrm{a}}T_{\mathrm{o}}\ln\left(\frac{p_{\mathrm{out}}}{p_{\mathrm{o}}}\right)\end{aligned} \tag{9}$$

where $c_{\mathrm{p,\,v}}$ is the specific heat capacity of water vapor, T_{out} is the supply outlet dry bulb temperature (cooled air temperature), p_{out} is the supply outlet pressure, p_{o} is the dead state pressure, and ϖ is the mole fraction ratio of the inlet condition.

Exergy loss rate is given by

$$\mathrm{Ex_{loss}} = Q_{\mathrm{c}}\left[1 - \left(\frac{T_{\mathrm{o}}}{T_{\mathrm{in}}}\right)\right] \tag{10}$$

where Q_{c} is the cooling obtained by fogging given by

$$Q_{\mathrm{c}} = m_{\mathrm{a}}C_{\mathrm{p}}(T_{\mathrm{in}} - T_{\mathrm{out}}) \tag{11}$$

Exergy destruction rate is computed as

$$\mathrm{Ex_{dest}} = \mathrm{Ex_{in}} - \mathrm{Ex_{out}} - \mathrm{Ex_{loss}} \tag{12}$$

The exergy efficiency is obtained as

$$\psi = \frac{\mathrm{Ex}_{\mathrm{out}}}{\mathrm{Ex}_{\mathrm{in}}} = \frac{\mathrm{Ex}_{\mathrm{out,\,a}}}{\mathrm{Ex}_{\mathrm{in,\,a}} + \mathrm{Ex}_{\mathrm{in,\,w}}} \tag{13}$$

Any method on energy savings must ensure minimal negative effects such as damage to environment (Rosen et al. (2008)). A sustainability assessment of the system is carried out by computing a sustainability index (SI) on the basis of exergy efficiency as

$$\mathrm{SI} = \frac{1}{1 - \psi} \tag{14}$$

4 Results and Discussions

In the present study, a thermodynamic analysis is done on an inlet air cooling system of a 9 MW turbocompressor, making use of the exergy computations. The measured air flow rate was 7650 m^3/h. The compressor pressure ratio was 8. Exergy input rate, exergy output rate, exergy loss rate, exergy destruction rate, and exergy efficiency were calculated with five different dead state temperatures and five different dead state relative humidities. The numerical results of the exergy analysis are quite strongly affected by the selection of the dead state conditions. There is a lack of convention on the selection of dead state conditions.

Minimum possible temperature attainable with any evaporative cooling system is the wet bulb temperature corresponding to the given inlet conditions of air. Hence, the dead state temperatures were chosen between the WBT and the inlet air temperature. The dead state relative humidity was fixed at 50%.

The maximum exergy input, output, and loss rates were computed as 25.0319 kW, 8.8969 kW, and 7.2991 kW corresponding to the dead state temperature of 30 °C. The maximum exergy destruction rate was 9.0223 kW at 38 °C. When the dead state temperature was same as the inlet air temperature, the exergy loss is zero.

The variation in exergy rates with dead state temperatures is plotted in Fig. 3, and the variation with different dead state relative humidities are shown in Fig. 4. Exergy rates are plotted against the dead state conditions. The dead state temperature was fixed at 30 °C for this set of computations. The maximum exergy input, output, and loss rates were computed as 95.37 kW, 63.03 kW, and 7.3 kW corresponding to the dead state relative humidity of 20%. The maximum exergy destruction rate was 25.04 kW at 20%. Exergy input rates of the inlet fogging systems consist of the inlet air and water droplets. Exergy input rates of inlet air and water droplets are given in Fig. 5. The maximum value of exergy input rate for inlet air and water was computed as 12.54 kW and 12.75 kW at 30 °C and 38 °C, respectively, for Case 1 (different dead state temperatures) and 66.47 kW and

Fig. 3 Exergy rates of with dead state temperatures

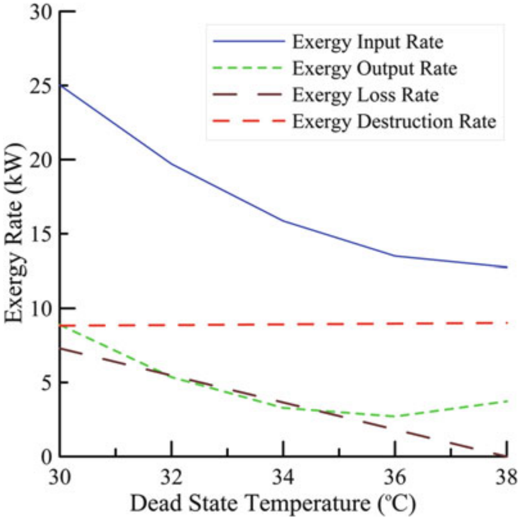
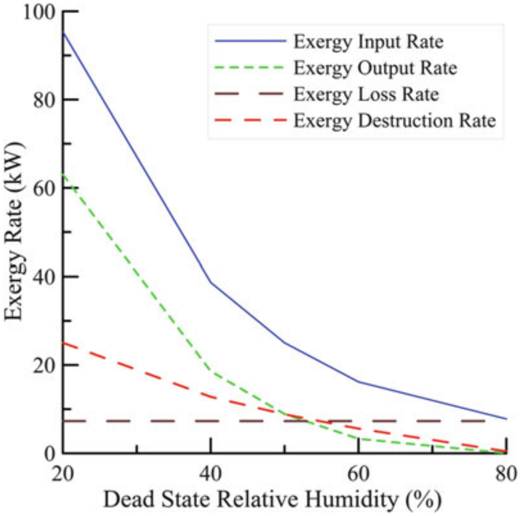


Fig. 4 Exergy rates with dead state relative humidity



28.9 kW at 20% relative humidity for Case 2 (different dead state relative humidities).

The exergy efficiency is plotted against the dead state temperature in Fig. 6. The relative humidity was fixed as 50%. Although maximum energy savings are possible at higher temperatures, maximum exergy efficiency is computed as 35.54% at the dead state temperature of 30 °C, while the minimum is at 36 °C.

The sustainable index computation is shown in Tables 1 and 2. Sustainable index depends on exergy efficiency. The maximum value for sustainable index is obtained for dead state temperature 30 °C and relative humidity 20%. The system is more sustainable at 30 °C and lower relative humidities.

Fig. 5 Exergy input rates with dead state temperatures

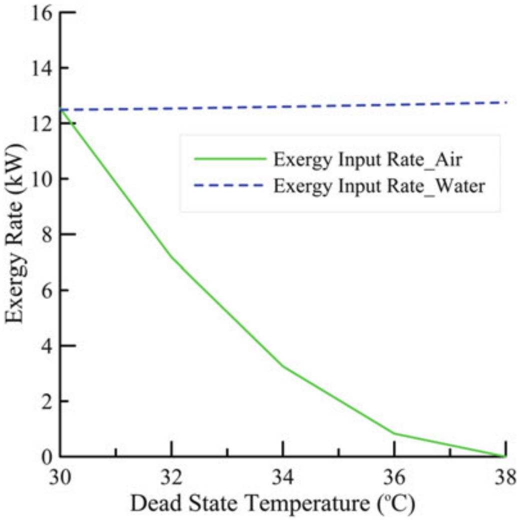


Fig. 6 Exergy efficiency with dead state temperatures

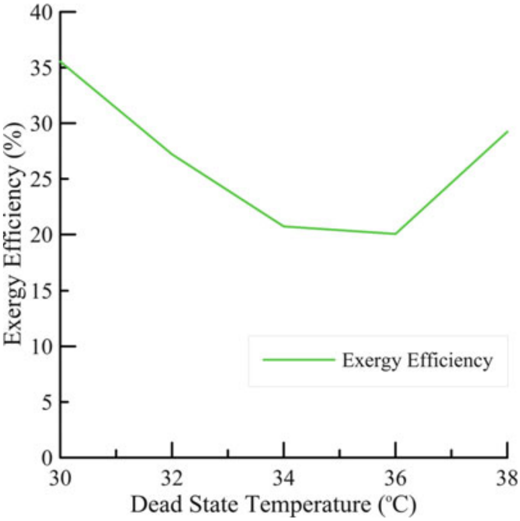


Table 1 Sustainability index for different dead state temperatures

Dead state temperatures (°C)	Exergy efficiency (%)	SI
30	35.54	1.55
32	27.20	1.37
34	20.73	1.26
36	20.05	1.25
38	29.23	1.41

Table 2 Sustainability index for different dead state relative humidities

Dead state R. H. (%)	Exergy efficiency (%)	SI
20	66.09	2.95
40	48.07	1.93
50	35.54	1.55
60	20.34	1.26
80	0.40	1.00

5 Conclusions

Exergy analysis was conducted on the inlet air cooling system for a turbocompressor. Exergetic parameters are strongly influenced by dead state conditions. The present analysis considered different dead state temperatures and dead state relative humidities. Exergy input rates decrease with increase in dead state conditions (T_o and ϕ_o). The exergy loss rate is inversely proportional to the dead state temperature. However, there is no change in the exergy loss rate with different relative humidity values.

The exergy destruction rate increases with increase in dead state temperature and decreases with increase in dead state relative humidity. Exergy efficiency is found to be inversely proportional to the dead state relative humidities and a maximum at the dead state temperature of 30 °C. Sustainability assessment was performed by computing sustainability index from exergy efficiency. Highest sustainability index was obtained for dead state temperature of 30 °C and dead state relative humidity of 20%.

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