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Article

Exergy Analysis of Overspray Process in Gas Turbine Systems

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Abstract: Gas turbine power can be augmented by overspray process which consists of inlet fogging and wet compression. In this study exergy analysis of the overspray process in gas turbine system is carried out with a non-equilibrium analytical modeling based on droplet evaporation and the second law of thermodynamics. This work focuses on the effects of system parameters such as pressure ratio, water injection ratio, and initial droplet diameter on exergetical performances including irreversibility and exergy efficiency of the process. The process performances are also estimated under the condition of saturated water injection ratio above which complete evaporation of injected water droplets within a compressor is not possible. The results show that the irreversibility increases but the saturated irreversibility decreases with increasing initial droplet diameter for a specified pressure ratio.

Keywords: water injection; droplet evaporation; overspray; gas turbine; exergy

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1. Introduction

The efficient use of energy resources has become increasingly important in order to ensure a strong and stable world economy, since it has become apparent that non-renewable energy sources are finite and are in danger of depletion to various degrees in the not too distant future. In recent years efficiency improvements have been achieved at various stages of the fuel-to-electricity conversion process, and a significant amount of research efforts has been spent on improving the conversion efficiency of the conventional technologies of power generation, especially in the area of gas turbines [1,2]. Humidified gas turbines that use gas-water mixture as the working fluid have been identified to have the potential of combined cycle efficiencies with relatively low cost. The application of evaporative cooling reduces compression work and enables recuperation or enhances the power production with same compression work [3,4]. In humidified gas turbines water can be injected at various positions such as system inlet duct, compressor inlet or outlet, and those techniques may be stated as inlet fogging, wet compression and after fogging, respectively.

Power output of gas turbine decreases with increased temperature of the inlet air due to reduced air density and mass flow rate. Kakaras *et al*. [5] showed that decreases in thermal efficiency and power output for a temperature of 40 °C and a relative humidity of 45% are 1.66% and 14.48%, respectively, when compared to ISO standard condition (15 °C, 60% RH). The evaporative cooling of air by inlet fogging is a well proven technology for enhancing the power of gas turbine engines. Performance specifications of gas turbines show that the reduced inlet temperature increases the capacity and reduce the heat transfer rate. Many researchers as Chaker *et al*. [6–8], Utamura [9], Bhargava and Mehr-Homji [10], Belarbi *et al*. [11], Yang *et al*. [12], Farzaneh-Gord and Deymi-Dashtebayaz [13], and Kim *et al*. [14] have conducted experimental or analytical studies on the inlet fogging in gas turbine engines, and achieved significant improvement at various aspects of the technology including methods of generating, controlling, and measuring sprays as well as the non-equilibrium modeling of the transient fogging process.

In the inlet fogging process the water injection at approximately 1% of the air mass flow rate is used, and higher injection rates can supply additional cooling. If water droplets are injected into a compressor inlet, wet compression occurs inside the compressor and higher injection rates are possible compared to inlet fogging. Utamura [15] showed experimentally that 1% of injection ratio in wet compression leads to 8% increase in power delivery. Wet compression in gas turbines has been thoroughly investigated by many researchers as Zheng *et al*. [16], White and Meacock [17], Kim and Perez-Blanco [18], Perez-Blanco *et al*. [19], Bracco *et al*. [20], Roumeliotis and Mathioudakis [21], Jonsson *et al*. [22], Goldborough *et al*. [23]. Kim *et al*. [24] developed a modeling for the transient operations for the non-equilibrium wet compression process based on droplet evaporation and obtained the analytic expressions with algebraic equations as solutions. Due to compression with intercooling, overspray inlet cooling can increase power more than inlet fogging. Chian *et al*. [25] and Sanyaye *et al*. [26,27] studied the effects of evaporative cooling process occurring in both compressor inlet duct (inlet fogging) and inside the compressor (wet compression).

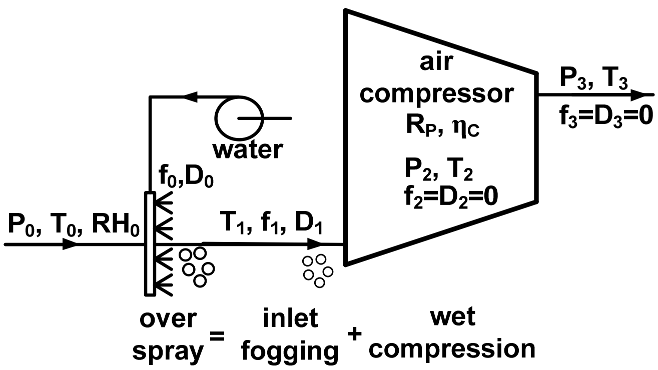
The exergy analysis is well suited for furthering the goal in achieving more effective energy resource use, since it enables the location, cause, and true magnitude of waste and loss to be determined [28,29]. Huaedogan *et al*. [30] dealt with the performance analysis and evaluation of a novel desiccant cooling system using exergy analysis method. Ehyaei *et al.* [31] investigated the effects of inlet fogging system on the first and second law efficiencies for a typical power plant. Kim *et al*. [32] carried out exergy analysis of simple and regenerative gas turbine cycles with wet compression.

In this study exergy analysis of the overspray process occurring in both inlet fogging and wet compression is carried out by using an analytical modeling based on combination of droplet evaporation and mean-line calculation [17,24]. The goal of the study is to investigate the potentials of gas turbine systems with overspray fogging, which can be applied to generic compressors. Effects of pressure ratio, water injection ratio, and initial droplet diameter are investigated parametrically on the irreversibility as well as exergy efficiency of the process. The performances of the process are also examined under the condition of maximum water injection ratio at which all the injected water droplets evaporate completely inside a compressor.

2. System Analysis

The overspray process consists of inlet fogging and wet compression processes, as illustrated in Figure 1. Let subscript 0 represent the state at inlet duct of gas turbine system where inlet fogging takes place, while the state at compressor inlet is denoted by subscript 1. Meanwhile, the subscripts 2 and 3 represent the states at completion of droplet evaporation and exit of compressor, respectively. Air at temperature of T_0, pressure of P_0, and relative humidity of RH_0 enters the inlet duct of the gas turbine system. At the same time, liquid water droplets are injected into the air stream with initial droplet diameter of D_0 at the water injection ratio of f_0, Note that the water injection ratio is defined as mass of liquid water per unit mass of dry air after the injection of water droplets. It is assumed that the small pressure drop occurring in the duct is negligible, thus the pressure of the system remains constant at its initial value during the inlet fogging process. Additionally, water droplets are assumed to be spherical and monodisperse and there are no interactions between the droplets during the process [18]. The present model of overspray process does not take into account the amount of water deposits on the walls of inlet ducts and compressor blade surfaces, which could adversely affect irreversibility and efficiency of the fogging process [8,33–35]. Also, the model introduced here in this study may not be accurate if there is substantial diffusion perpendicular to the mean streamlines in compressor channels.

Figure 1. Schematic of overspray process for gas turbine systems.



The saturated water injection ratio f_{0c} is defined as the maximum injection ratio that results in complete evaporation within the compressor. When water injection ratio f_0 is lower than f_{0c}, the injected droplets evaporate completely during the process and no liquid droplet leaves the compressor. Then we expect $f_3 = D_3 = 0$. On the contrary, when water injection ratio f_0 is higher than f_{0c}, the air becomes saturated and remained liquid water droplets leave the compressor along with air [14]. In this work the analysis is restricted to the cases of complete evaporation of injected droplets inside a compressor.

The compression process can be characterized by the parameter of compression rate, C, defined as Equation (1), and it is assumed that C has a constant value [18].

$$C = \frac{1}{P}\frac{dP}{dt} \tag{1}$$

$$\Delta t_c = \frac{\ln(R_p)}{C} \tag{2}$$

Here Δt_c is the compression time, $R_p = P_3 / P_1$ the pressure ratio, P_3 the pressure at compressor exit. Irrespective of whether phase change is occurring, aerodynamic performance may be characterized by polytropic efficiency of compressor η_c as [17]:

$$dh = \frac{vdP}{\eta_c} \tag{3}$$

where P is the air pressure, and h and v are specific enthalpy and volume of humid air, respectively.

The changing rate of mass and energy of the droplets can be written with the quasi-steady relations as [11]:

$$\frac{df}{dt} = -A \cdot J \tag{4}$$

$$f \cdot c_{pw} \cdot \frac{dT_s}{dt} = A \cdot (q_S - q_L) = A \cdot (q_S - h_{fg} \cdot J) \tag{5}$$

Here f is the mass of water droplets per unit mass of dry air, A the total surface area of water droplets, T_s the temperature of water droplets, J the vapor mass flux away from the droplets, q_L the latent heat flux due to droplet evaporation, q_S the sensible heat flux due to diffusion or convection, and h_{fg} the latent heat of vaporization.

In this work heat and mass fluxes on the surface of spherical water droplets are expressed with Stokes model as follows [24]:

$$q_S = \frac{2 \cdot k}{D} \cdot (T - T_s) \tag{6}$$

$$J = \frac{2 \cdot D_v \cdot k}{D \cdot R_v} \cdot \left(\frac{P_s}{T_s} - \frac{P_v}{T} \right) \tag{7}$$

where k is the thermal conductivity of air, D_v the mass diffusion coefficient of water vapor in air, R_v the gas constant of water vapor, and P_s is the saturated pressure at T_s. The solution can be approximated by using the temperature-averaged constant c_{wet} and temperature-averaged polytropic coefficient n_{wet} as [24]:

$$c_{wet} = \frac{n_{wet}}{n_{wet} - 1} = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} \left(\frac{\eta}{R_a + \omega \cdot R_v} \cdot \frac{dh}{dT} \right) dT \tag{8}$$

Then relations of pressure, volume, and temperature can be denoted by polytropic process as [24]:

$$Pv^{n_{wet}} = \text{constant} = P_1 v_1^{n_{wet}} \tag{9}$$

$$c_{wet} = \frac{n_{wet}}{n_{wet} - 1} = \eta \frac{B_3}{A_3} (1 - \beta_1 \Phi) \tag{10}$$

$$\Phi = \frac{1}{6a}\left[2(a-b)\ln\left(\frac{a-1}{a}\right) + (2a+b)\ln\left(\frac{a^2+a+1}{a^2}\right) - 2\sqrt{3}b\left\{\tan^{-1}\left(\frac{a+2}{\sqrt{3}a}\right) - \frac{\pi}{6}\right\}\right] \tag{11}$$

If once T_2 is determined, the evaporation time t_{evap} can be obtained as

$$t_{evap} = \frac{c_{wet}}{C}\ln\left(\frac{T_2}{T_1}\right) \tag{12}$$

The detailed modeling process and the related coefficients can be obtained in [24]. The analysis is performed by the programming spreadsheet of graphical mathematics software (MathCAD).

The exergy of a stream is defined as the property with the meaning of maximum useful work available when the stream evolves reversibly to reach equilibrium with the environment. Specific exergy e is defined as

$$e = h - h_{ref} - T_{ref}\left(s - s_{ref}\right) \tag{13}$$

where s is specific entropy and subscript *ref* denotes the reference dead state. Then specific compression work w_c, irreversibility of inlet fogging process I_0, total irreversibility I_{tot}, exergy efficiency η_{ex} are defined as follows [28,29]:

$$w_c = h_3 - h_1 \tag{14}$$

$$I_0 = e_0 - e_1 = T_{ref}\left(s_1 - s_0\right) \tag{15}$$

$$I_{tot} = e_0 + w_c - e_3 = T_{ref}\left(s_3 - s_0\right) \tag{16}$$

$$\eta_{ex} = \frac{\text{exergy increase}}{\text{work input}} = \frac{e_3 - e_0}{w_c} \tag{17}$$

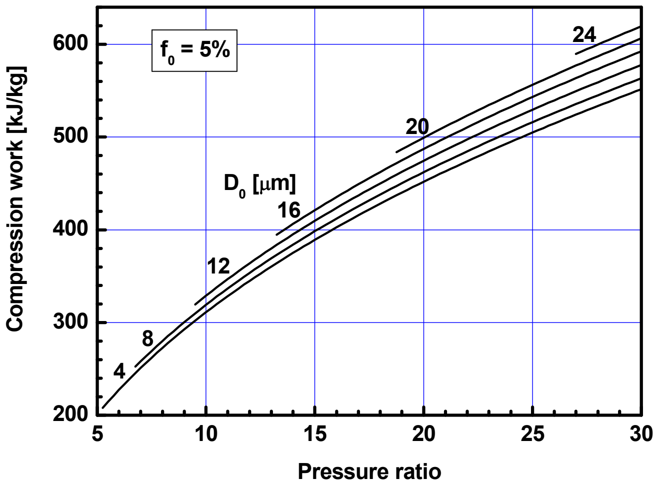
3. Results and Discussion

3.1. Effects of Pressure Ratio

The behavior of the overspray process depends on various system parameters such as the water injection ratio f_0, the pressure ratio R_p, the initial diameter of the droplets D_0, the compression rate C, the polytropic compression efficiency η and the ambient conditions. The basic data for the analysis are as follows: compression rate C = 100 s^{-1}, polytropic compression efficiency η_c = 80%, water injection ratio f_0 = 5%, pressure ratio R_p = 20, initial pressure $P_0 = P_{ref}$ = 1 atm, inlet temperature $T_0 = T_{ref}$ = 15 °C, and relative humidity at inlet RH_0 = 60% (ISO condition).

Effects of pressure ratio on the compression work are shown in Figure 2 for various initial droplet diameters ranging from 4 to 24 μm at water injection ratio of f_0 = 5%. The compression work increases with initial droplet diameter as well as with pressure ratio. It is expected that larger but fewer droplets evaporate more slowly than smaller droplets and the corresponding cooling rate of air due to droplet evaporation is lower than that of smaller droplets. Since the scope of analysis in this work is restricted to the case where all the injected droplets evaporate completely inside a compressor, the evaporation time t_{evap} should be less than the compression time Δt_c. Then for a given water injection ratio, there exists a lower limit value of pressure ratio under which the complete evaporation of water droplets inside the compressor is impossible. This limit value of pressure ratio increases with initial droplet diameter.

Figure 2. Effects of pressure ratio and initial droplet diameter on the compression work at water injection ratio f_0 = 5%.



Variations of irreversibility during the process I_{tot} and the irreversibility ratio of inlet fogging process to total process I_0/I_{tot} are shown in Figures 3 and 4, respectively, against pressure ratio for various initial droplet diameters. As observed in the figures, irreversibility or exergy destruction during the process I_{tot} increases with pressure ratio, for higher pressure ratio results in larger entropy generation during the compression process. The irreversibility ratio of inlet fogging is found to be quite small and it decreases with pressure ratio, since irreversibility of wet compression increases whereas irreversibility of inlet fogging remains unchanged. As initial droplet diameter increases for a fixed pressure ratio and water injection ratio, the irreversibility of the process increases but the irreversibility ratio of inlet fogging decreases. For example, for R_p = 20, the values of the irreversibility are 108.7, 113.7, 119.7, 125.7, and 131.3 kJ/kg for initial droplet diameter of 4, 8, 12, 16, and 20 μm, respectively.

Figure 3. Effects of pressure ratio and initial droplet diameter on total irreversibility at water injection ratio f_0 = 5%.

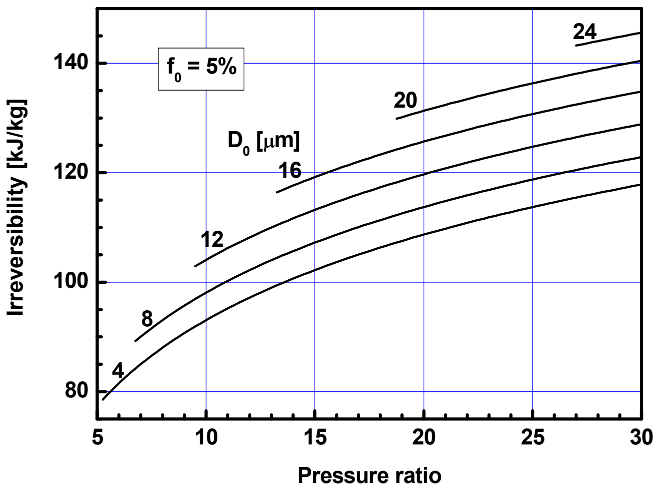
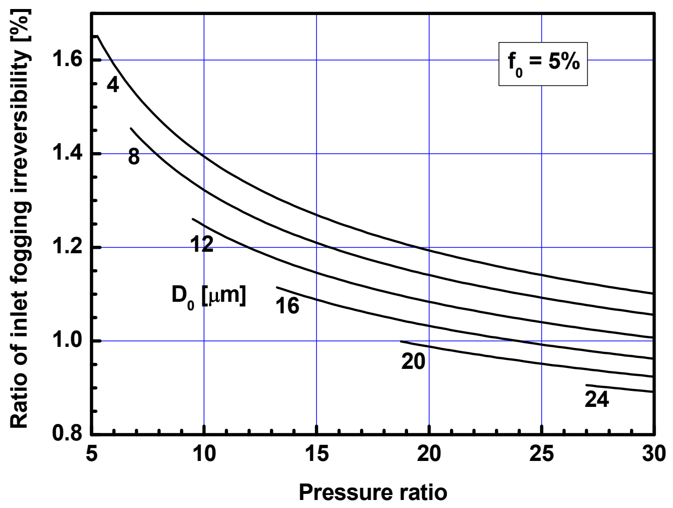
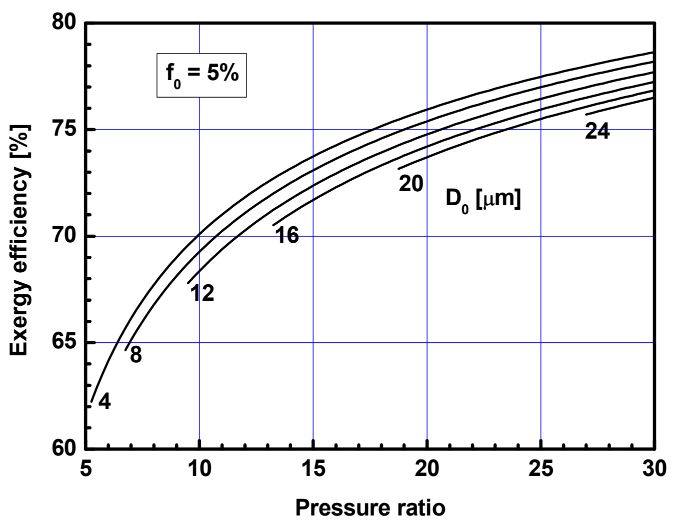


Figure 4. Effects of pressure ratio and initial droplet diameter on the ratio of inlet fogging irreversibility to total irreversibility at water injection ratio f_0 = 5%.



Effects of pressure ratio on the exergy efficiency are shown in Figure 5 for various initial droplet diameters at water injection ratio of 5%. Exergy efficiency is defined as the ratio of increased exergy to input work as Equation (17). As pressure ratio increases for a fixed value of initial droplet diameter, the exergy efficiency grows, which means that both the compression work and irreversibility increase with pressure ratio but increasing of irreversibility is less dominant than that of compression work. On the other hand, exergy efficiency decreases with increasing initial droplet diameter for a fixed pressure ratio, which means that both the compression work and irreversibility increase with initial droplet diameter but increasing of irreversibility is less dominant than that of compression work. Therefore, the results show that the overspray process becomes exergetically more efficient as pressure ratio increases or initial droplet diameter becomes smaller.

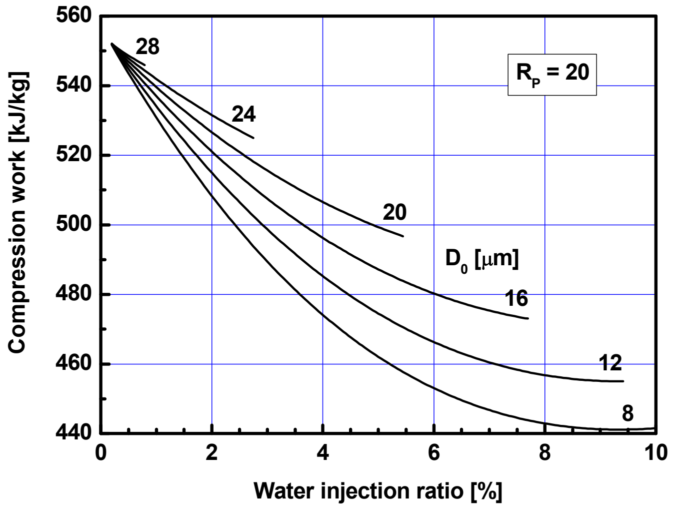
Figure 5. Effects of pressure ratio and initial droplet diameter on the exergy efficiency at water injection ratio f_0 = 5%.



3.2. Effects of Water Injection Ratio

Figure 6 shows variations of the compression work with respect to water injection ratio for various initial droplet diameters at pressure ratio of R_p = 20. The range of water injection ratio tested here is up to 10%, which is in fact much higher than typical cases of gas turbine water injection. However, it should be noted that this study is seeking potential of overspray process which may allow higher water injection ratio than usual water injection process. Showing the benefit of water droplet injection, increasing water injection ratio reduces the compression work for a fixed value of initial droplet diameter, since evaporation of more droplets results in greater absorption of latent vaporization heat from air and the corresponding cooling rate of air due to droplet evaporation is higher than that of fewer droplets. Similarly with the aforementioned lower limit value of pressure ratio, the water injection ratio has a higher limit value above which the complete evaporation of water droplets inside the compressor is impossible. The limit value of water injection ratio decreases with increasing initial droplet diameter.

Figure 6. Effects of water injection ratio and initial droplet diameter on the compression work at pressure ratio R_p = 20.



For the pressure ratio R_p = 20, Figures 7 and 8 show the variations of irreversibility during the process I_{tot} and the irreversibility ratio of inlet fogging process to total process I_0/I_{tot}, respectively, with respect to water injection ratio for various initial droplet diameters. The total irreversibility during the overspray process I_{tot} increases almost linearly with water injection ratio, for higher water injection ratio leads greater cooling of air temperature and consequently greater irreversibility during the compression process. The irreversibility ratio of inlet fogging decreases with water injection ratio, which states that the irreversibility of wet compression is dominant, compared to inlet fogging process, and the tendency becomes deepened as water injection ratio increases.

Effects of water injection ratio on the exergy efficiency are shown in Figure 9 for various initial droplet diameters at pressure ratio of 20. As water injection ratio increases for a fixed value of initial droplet diameter, the exergy efficiency decreases almost linearly, since the compression work decreases but irreversibility increases. For example, for R_p = 20 and D_0 = 12 μm, the exergy efficiencies are 86%, 83%, 80%, 77%, 75%, 72%, 69%, 67% and 64% respectively when water injection ratio increases from 1% to 9%.

Figure 7. Effects of water injection ratio and initial droplet diameter on total irreversibility at pressure ratio $R_p = 20$.

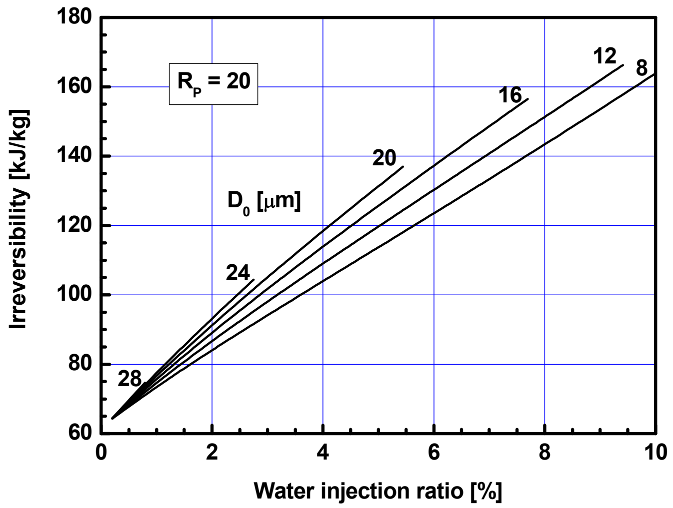


Figure 8. Effects of water injection ratio and initial droplet diameter on the ratio of inlet fogging irreversibility to total irreversibility at pressure ratio $R_p = 20$.

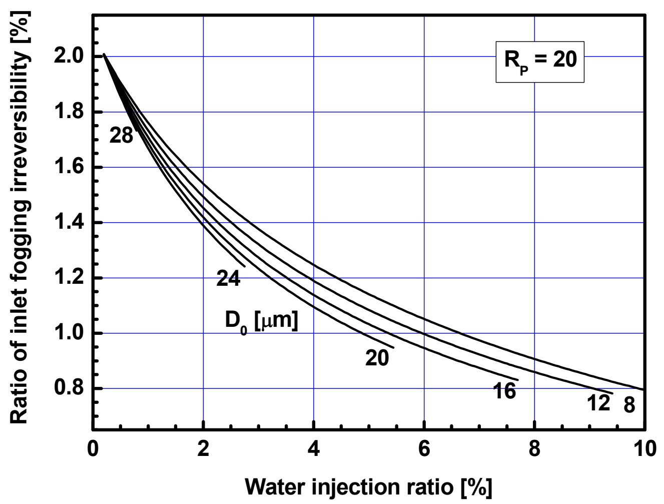
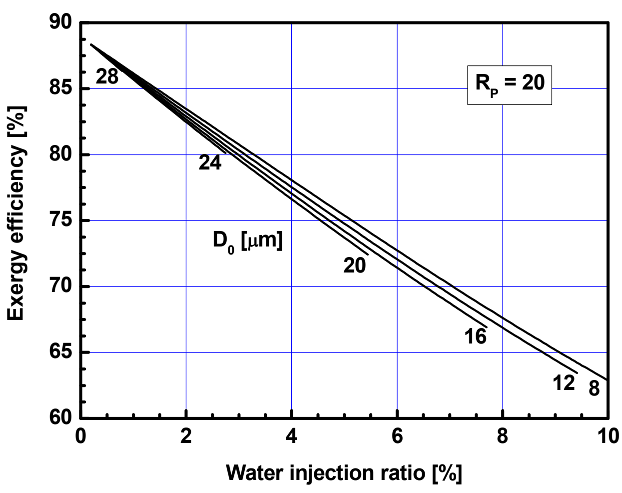


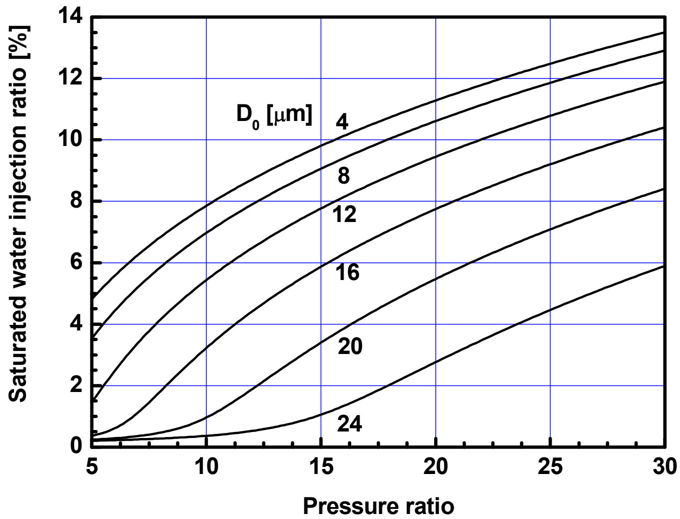
Figure 9. Effects of water injection ratio and initial droplet diameter on the exergy efficiency at pressure ratio $R_p = 20$.



3.3. Results with Saturated Water Injection Ratios

As previously mentioned, the analysis in this work is restricted to the cases of complete evaporation of injected droplets inside a compressor. Hence for a specified pressure ratio and an initial droplet diameter, there exists a maximum possible water injection ratio for complete evaporation of injected droplets within a compressor and it is referred to as the saturated water injection ratio in this study. Figure 10 shows the saturated injection ratio depending on pressure ratio and initial droplet diameters. As expected, the saturated injection ratio increases with increasing pressure ratio and decreases with increasing initial droplet diameter. Particularly when the initial droplet diameter becomes large, the saturated injection ratio approaches a very small value.

Figure 10. Effects of pressure ratio and initial droplet diameter on the saturated water injection ratio.



The variations of saturated irreversibility are shown in Figure 11 with respect to pressure ratio for various initial droplet diameters. The saturated irreversibility of the process increases with water injection ratio for a fixed value of initial droplet diameter. Furthermore, its increasing rate is higher than that of the case of constant water injection ratio. This is because as the pressure ratio increases, the saturated water injection ratio increases, and the corresponding cooling rate and irreversibility become larger. At a fixed value of pressure ratio, the saturated irreversibility decreases with increasing initial droplet diameter, which is a reverse phenomenon to the case of constant water injection ratio as is seen in Figure 3. This is because as follows. The irreversibility increases with initial droplet diameter but decreases with water injection ratio. The saturated water injection ratio increases with pressure ratio, and this decreasing effect is more significant to the increasing effect by initial droplet diameter. Figure 12 shows the effects of pressure ratio on the ratio of saturated irreversibility of inlet fogging process to total saturated irreversibility for various initial droplet diameters. The irreversibility ratio decreases with pressure ratio but increases with initial droplet diameter. The reasons are similar to those of previous case of irreversibility.

Figure 11. Effects of pressure ratio and initial droplet diameter on total irreversibility at the saturated water injection ratio.

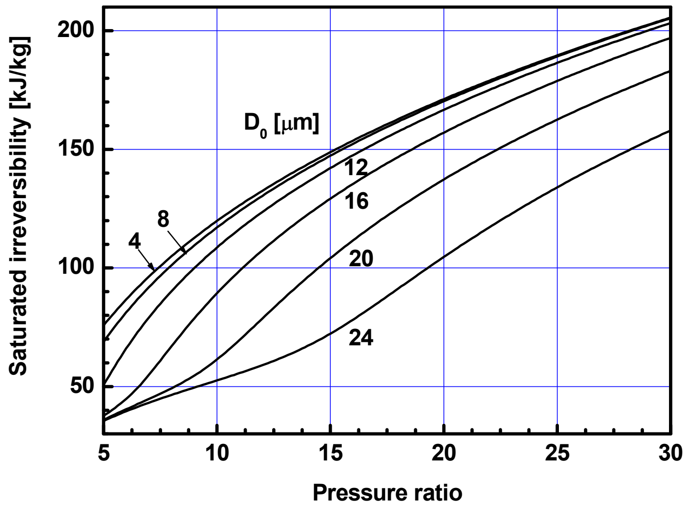
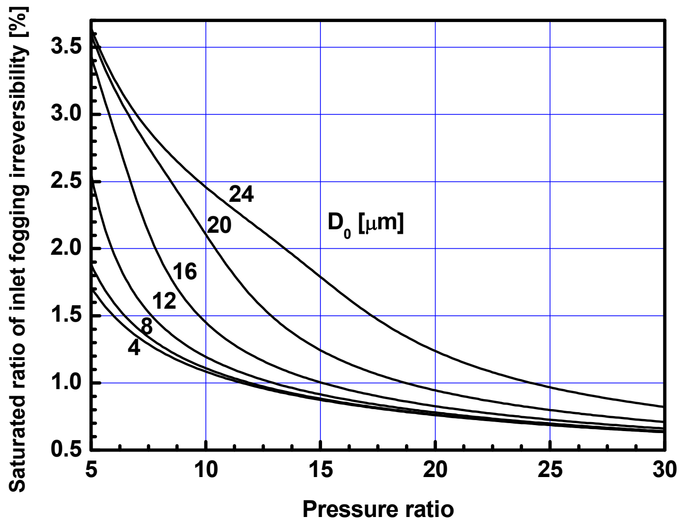
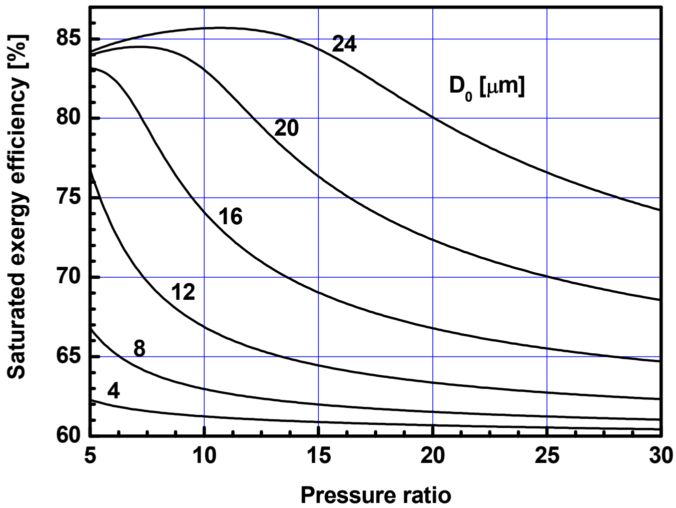


Figure 12. Effects of pressure ratio and initial droplet diameter on the ratio of inlet fogging irreversibility to total irreversibility at the saturated water injection ratio.



Effects of water injection ratio on the saturated exergy efficiency are shown in Figure 13 for various initial droplet diameters. Exergy efficiency increases with initial droplet diameter for a fixed pressure ratio, since the saturated water injection ratio increases as initial droplet diameter increases. As water injection ratio increases for a fixed value of initial droplet diameter, the exergy efficiency decreases for lower initial droplet diameters, however, may have a peak value for higher initial droplet diameters. The reason is as follows. Exergy efficiency increases with pressure ratio for a fixed water injection ratio, but on the contrary decreases with water injection ratio for a fixed pressure ratio. When initial droplet diameter is small, the decreasing effect due to increase in saturated water injection is dominant, so the saturated exergy efficiency decreases. But when initial droplet diameter is large, the decreasing effect due to increase in saturated water injection is comparable with the increasing effect due to pressure ratio, so there may exist a peak value.

Figure 13. Effects of pressure ratio and initial droplet diameter on the exergy efficiency at the saturated water injection ratio.



4. Conclusions

In this study exergy analysis is carried out on the overspray process which consists of inlet fogging and wet compression in gas turbine systems by using a non-equilibrium analytical modeling based on the evaporation of injected liquid droplets. Analysis in this work is restricted to complete droplet evaporation case only. Most significant system parameters of the system are water injection ratio, initial droplet diameter, and pressure ratio. Special attention is paid to the effects of system parameters on irreversibility and exergy efficiency of the process. The process performances are also estimated under the condition of saturated water injection ratio. Results show that the irreversibility increases but the saturated irreversibility decreases with increasing initial droplet diameter for a specified pressure ratio.

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