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Influence of Ambient Condition on Performance of Wet Compression Process

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***Abstract*—**Gas turbine systems with wet compression have a potential for future power generation, since they can offer a high efficiency and a high specific power with a relatively low cost. In this study influence of ambient condition on the performance of the wet compression process is investigated with a non-equilibrium analytical modeling based on droplet evaporation. Transient behaviors of droplet diameter and temperature of mixed air are investigated for various ambient temperatures. Special attention is paid for the effects of ambient temperature, pressure ratio, and water injection ratios on the important wet compression variables including compressor outlet temperature and compression work. Parametric studies show that downing of the ambient temperature leads to lower compressor outlet temperature and consequently lower consumption of compression work even in wet compression processes.

***Keywords*—**water injection, droplet evaporation, wet compression, gas turbine, ambient condition

I. INTRODUCTION

DUE to the decreasing fossil fuel resources and increasing fuel price but rapidly increasing energy demand, the efficient use of energy resources and applications is of great importance and has been attracting much attention in recent years. Gas turbine power plants are widely used all over the world for electricity generation [1-3]. One of the solutions can be using the humidified gas turbines which mean the systems in which water or steam is injected at various positions to enhance their power output. In these systems evaporative cooling is a key process which can be classified as inlet cooling, exit cooling, and wet compression or continuous cooling [4-5].

Kim [6] investigated comparatively the water and steam injection gas-turbine systems of regenerative after-fogging gas-turbine systems (RAF), steam-injection gas-turbine systems (STIG), and regenerative steam-injection gas-turbine systems (RSTIG). Kim et al [7] established an analytical modeling which can simulate the transient inlet fogging process for both low and high fogging. They analyzed the cooling process using four simultaneous heat and mass transfer models: (A) diffusion, (B) natural convection, (C) Stokes convection, and (D) perturbed Stokes.

Wet compression is a process whereby liquid water droplets are injected at the entrance of a compressor, flow as aerosols with gas phase being compressed and heated, evaporate and cool continuously the surround gas inside the compressor.

The applied evaporative cooling reduces compression work and enables recuperation, especially in cycles with large pressure ratios. In addition, it increases the mass flow rate in the turbines, resulting in additional power production [8].

White and Meacock [9] take up the subject by simulating the effect of small water droplets in a compressor with two conceptions of equilibrium and non-equilibrium evaporation inside a compressor by assuming mean-line design. Zheng et al. [10] considered a thermodynamic model of the wet compression process. Kim et al [11-12] carried out energy and exergy analyses of the performance of gas turbine cycles with wet compression. Perez-Blanco et al. [13] investigated the general case of evaporatively-cooled compression with high-pressure refrigerants. Sa et al [14] investigated the effects of varying ambient temperature and show that the gas turbine loses 0.1% in terms of thermal efficiency for every K rise in ambient temperature above ISO conditions.

Recently Kim et al [15] developed a modeling for the transport operations for the non-equilibrium wet compression process based on droplet evaporation and obtaining the analytic expressions with algebraic equations as solutions. In this study, effects of ambient condition on the wet compression process are investigated based on the analytical modeling developed by Kim et al [15]. Wet compression variables such as compressor exit temperature or compression work are estimated for various pressure ratios, water injection ratios as well as ambient temperatures.

II. SYSTEM ANALYSIS

In this study it is assumed that air enters the compressor at T_1, P_1 and RH_1 and at the same time liquid droplets are injected into the air with initial droplet diameter of D_1 at a rate of f_1, mass of liquid per unit mass of dry air. The compression process can be characterized by the parameter of compression rate, C defined by [11]

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

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

Here Δt_c is the compression time, R_p the compression ratio, the pressure at compressor discharge, and it is assumed that C has a constant value. Irrespective of whether phase change is occurring, aerodynamic performance may be characterized by polytropic efficiency as [11].

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

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

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

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

Here I is the vapor mass flux away from the droplets, q_L the latent heat flux due to droplet evaporation, and q_S the sensitive heat flux due to convection. Here the initial temperature of the droplet is assumed to be same as that of air of T_1.

In this work heat and mass fluxes are expressed with Stokes model as follows [15]

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

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

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 [15]

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

Then relations of pressure, volume and temperature can be denoted by polytropic process as [15]

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

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

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

If once T_2 which is the temperature at evaporation completion is determined, the evaporation time can be obtained as

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

When the liquid droplets are evaporated completely, there remain no liquid droplets so that dry compression begins. Dry compression process can be expressed as polytropic process, too. Detail process and related coefficients are given in [15].

III. RESULTS AND DISCUSSIONS

In this study the basic data for analyses are initial pressure P_1 = 1 atm, inlet temperature T_1 = 15 °C, relative humidity at inlet, RH_1 = 60%, compression rate C = 200 s^{-1}, polytropic efficiency η = 90%, pressure ratio R_p = 15, and initial droplet diameter D_1 = 10 μm.

Fig. 1 shows the transient behaviors of the droplet diameter versus time for various ambient temperatures. After injection the droplet diameter decreases monotonically and its decreasing rate increases monotonically until the evaporation is complete. For a specified value of water injection ratio, the evaporation time needed for complete evaporation decreases with increasing ambient temperature. For example, evaporation times are 12.1 ms, 11.5 ms, 11.0 ms, 10.6 ms, 10.2 ms, and 9.9 ms for ambient temperatures of 5 °C, 15 °C, 25 °C, 35 °C, 45 °C, and 55 °C, respectively.

The transient behaviors of the air temperature versus time are shown in Fig. 2 for various ambient temperatures. The air temperature with wet compression increases with increasing time and pressure. However, its increasing rate is lower than that of dry compression due to evaporation of water droplets. But it can be seen from the figure that the increasing rate jumps abruptly after a certain time at which the compression process turns from dry to wet one due to complete evaporation of water droplets.

Fig. 3 shows variation of the air temperature at compressor exit with respect to pressure ratio for various ambient temperatures. It can be seen that for a fixed value of ambient temperature the exit air temperature increases with pressure ratio, since higher exit pressure leads to higher exit air temperature. For a fixed value of pressure ratio, the exit air temperature increases with increasing ambient temperature. In this work the analysis is restricted to complete evaporation case only to avoid modeling the liquid water downstream of the compressor.

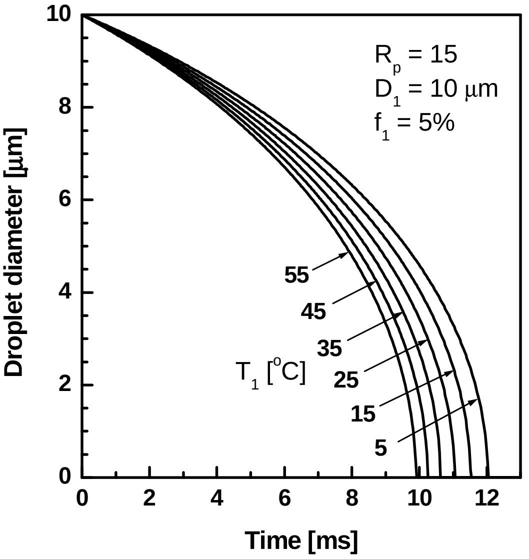

Fig. 1 Transient behaviors of droplet diameter for various ambient temperatures

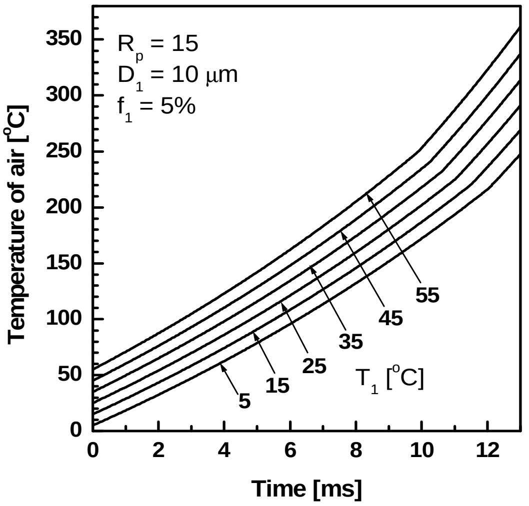

Fig. 2 Transient behaviors of air temperature for various ambient temperatures

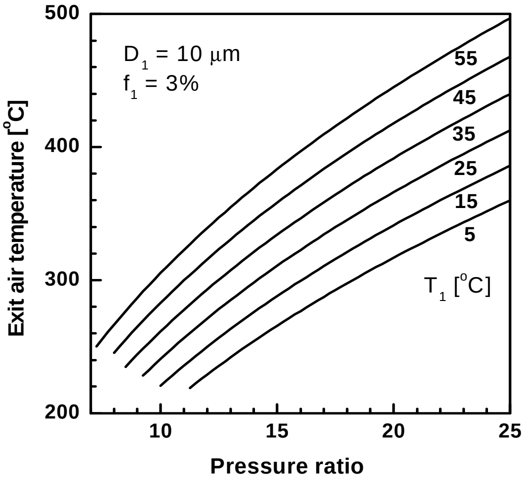

Fig. 3 Variations of exit air temperature with respect to pressure ratio for various ambient temperatures

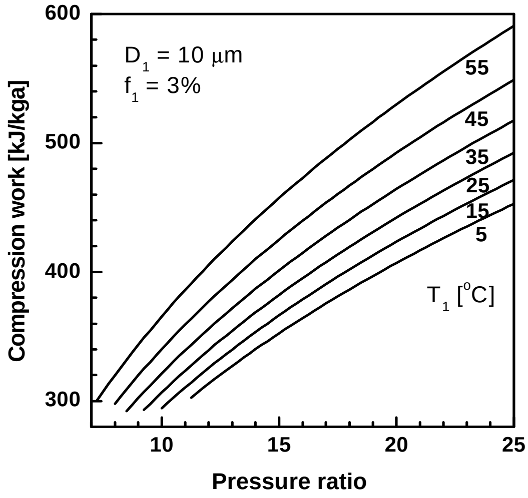

Fig. 4 Variations of compression work with respect to pressure ratio for various ambient temperatures

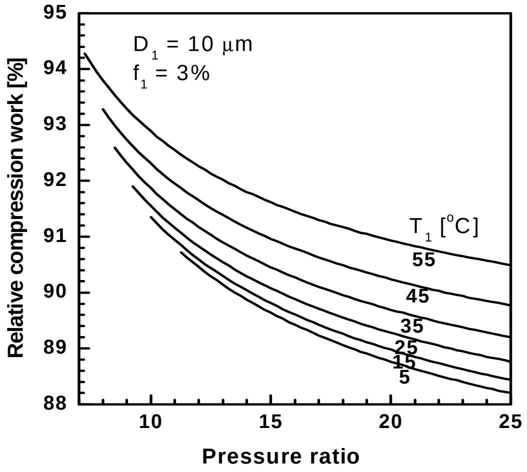

Fig. 5 Variations of relative compression work with respect to pressure ratio for various ambient temperatures

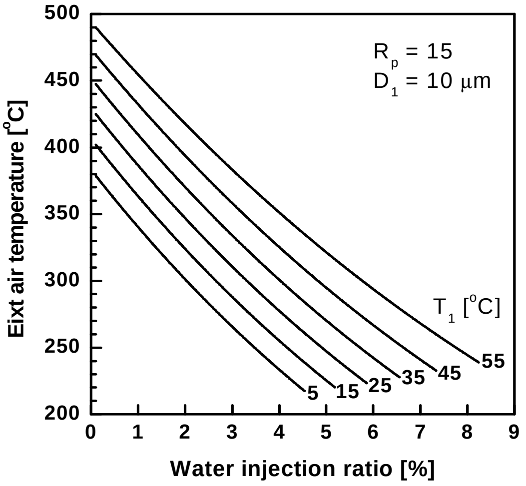

Fig. 6 Variations of exit air temperature with respect to water injection ratio for various ambient temperatures

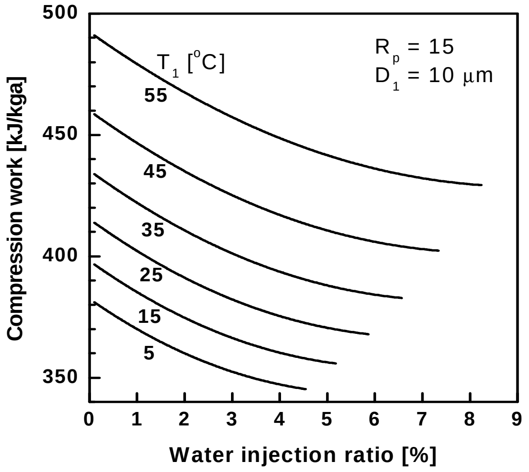

Fig. 7 Variations of compression work with respect to water injection ratio for various ambient temperatures

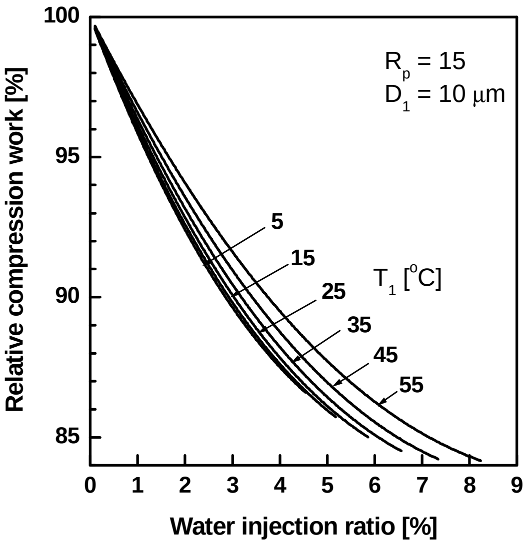

Fig. 8 Variations of relative compression work with respect to water injection for various ambient temperatures

Therefore when a pressure ratio is smaller than a certain value for a given ambient temperature, it is impossible for the droplets to evaporate within a compressor, which is excluded in this study. Thus, there exists a lower limit of pressure ratio for a given ambient temperature, and the limit of pressure ratio increases with decreasing the ambient temperature. Absolute and relative compression works are plotted against pressure ratio in Fig. 4 and Fig. 5 for various ambient temperatures. It is seen from Fig. 4 that for a specified ambient temperature the compression work increases with increasing pressure ratio. For a specified pressure ratio the compression work increases with increasing ambient temperature. For example when compression ratio is held at R_p = 25, compression works are 452.8 kJ/kg, 471.3 kJ/kg, 492.3 kJ/kg, 517.4 kJ/kg, 548.8 kJ/kg, 590.8 kJ/kg for ambient temperatures of 5 °C, 15 °C, 25 °C, 35 °C, 45 °C, and 55 °C, respectively.

The relative compression work is defined as the ratio of compression work under wet compression to that under dry compression. Fig. 5 shows that for a specified water injection ratio the relative compression work decreases with increasing compression ratio, since greater compression ratio leads to higher air temperature and consequently to greater driving force for droplet evaporation. As ambient temperature increases for a specified pressure ratio, the relative compression work increases, namely reduction of compression work due to water injection decreases as ambient temperature increases. For example when the pressure ratio is held at R_p = 25, relative compression works are 88.2%, 88.4%, 88.8%, 89.2%, 89.8% and 90.5% for ambient temperatures of 5 °C, 15 °C, 25 °C, 35 °C, 45 °C, and 55 °C, respectively.

Fig. 6 shows variation of the exit air temperature with respect to water injection ratio for various ambient temperatures. It can be seen from the figure that for a fixed value of ambient temperature the exit air temperature decreases with increasing water injection ratio, since higher water injection ratio leads to lower exit air temperature.

For a fixed value of water injection ratio, the exit air temperature increases with increasing ambient temperature. There exists an upper limit of water injection ratio above which complete evaporation is impossible for a given ambient temperature, and the limit of water injection ratio increases with increasing the ambient temperature. The exit air temperature drops about 35 °C for every 1% of water injection.

Compression works are plotted against water injection ratio in Fig. 7 for various ambient temperatures. The compression work decreases with increasing water injection ratio or decreasing ambient temperature. For example when compression ratio is held at 15, compression works decrease from 381.1 kJ/kg, 396.6 kJ/kg, 413.8 kJ/kg, 433.8 kJ/kg, 458.5 kJ/kg, 491.0 kJ/kg for dry compression to 347.2 kJ/kg, 360.4 kJ/kg, 375.4 kJ/kg, 393.8 kJ/kg, 417.0 kJ/kg, 448.8 kJ/k for wet compression of 4% at ambient temperatures of 5 °C, 15 °C, 25 °C, 35 °C, 45 °C, and 55 °C, respectively. Therefore, specific compression work falls 10 kJ/kg when water injection rate is raised 1%, and falls about 1.5 kJ/kg when ambient temperature falls 1 °C.

Relative compression work is plotted against water injection ratio in Fig. 8 for various ambient temperatures. The relative compression work decreases with increasing water injection ratio or decreasing ambient temperature, too. For example when the water injection ratio is held at 4%, relative compression works are 87.5%, 87.6%, 87.8%, 88.2%, 88.8% and 89.5% for ambient temperatures of 5 °C, 15 °C, 25 °C, 35 °C, 45 °C, and 55 °C, respectively.

IV. CONCLUSION

In this study effects of ambient temperatures on the performance of wet compression process in gas turbine systems are investigated by using an analytical modeling based on the evaporation of injected liquid droplets. The heat and mass transfer of the process are modeled with Stokes convection. To avoid modeling the liquid water downstream of the compressor, the analysis in this work is restricted to complete evaporation case only. Most significant system parameters of the system are water injection ratio, pressure ratio, and ambient temperature. Transient behavior of droplet diameter is investigated for various ambient temperatures. Furthermore effects of system parameters are thoroughly investigated on air temperature at compressor exit, absolute and relative compression work. For the typical conditions of system parameters, it is estimated that the exit air temperature drops about 35 °C for every 1% of water injection, the specific compression work falls about 10 kJ/kg when water injection rate is raised 1%, and falls about 1.5 kJ/kg when ambient temperature falls every 1 °C.

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