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Thermo-Fluid Analysis on the Efficiency of Wet Compression Process

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ABSTRACT

Wet compression has been well known as a promising technology to effectively increase the power output of the gas turbine engine by introducing fine droplets of water into the compressor stages. This lessens the temperature rise throughout the compression process of gas, thus leading to the reduction in the compressor work. A considerable amount of research on the wet compression process has been performed to date, but the detailed compression process of the two-phase gas media and fine droplets is not well understood yet. In the present study, the thermo-fluid analysis has been done on a simple flow model that has a spherical droplet of water inside a cylinder-piston system. The model is validated by using a quasi-steady D^2 – Law of evaporation model. The compression rate is varied by employing the piston movement under various flow conditions such as percentage of overspray, water droplet diameter, relative humidity, and temperature. The results obtained show that for a higher percentage of overspray, smaller droplet diameters and a slower compression rate the efficiency obtained is high. Which results in lesser compressor work. The effects of compression rate, droplet diameter, overspray, and the efficiency of the wet compression have been explained and analyzed in detail.

Keywords: Overspray; Latent heat; Evaporation rate; Wet compression; Compressor power saving; Compression rate.

NOMENCLATURE

A, B, C	antoine constants
C_p	specific heat capacity
DC	Diffusion Coefficient
D	diameter of the cylinder
Da	dry ai
d_r	diameter of the droplet
d	droplet
dry	dry compression
ER	Evaporation Rate
K	thermal conductivity
L	specific latent heat
LH	latent heat
M	mass
N_d	number of droplets
OS	overspary
P	pressure
Q	heat conducted
Q	heat flux
RH	Relative Humidity
R	specific gas constant
W	work done
S	specific entropy
T	temperature
T	time
v	vapor
vd	saturated vapor region
V	volume
w	water
Wet	wet compression
x	specific humidity
ΔM	evaporated mass
Δt	time step
ΔV	volume Increment
ρ	density
η	efficiency

1. INTRODUCTION

Wet compression technology is determined to be one of the most efficient means to enhance the performance of the gas turbine. In recent years, the wet compression process has been extensively used to reduce the temperature rise during the compression of the working gas. Wet compression is the process of spraying water in the air when compression takes place. As the sprayed water droplet evaporates during the compression process, the water droplets absorb the heat produced during the compression process, which produces a cooling effect in the system by which it subjects to a reduced compression work and which in turn improves the output power of the gas turbine. The wet compression process is cost-effective and less complex than any other cooling technique in the compressor.

There are a certain number of other techniques for heat reduction in the compressor. One of the techniques is the inlet fogging method in which the temperature of the air-water mixture will be reduced before the inlet of the compressor. Bhargava and Meher-Homji (2005) presented a study on the high-pressure inlet fogging system at higher ambient temperatures and lower humidity. The effect of the water droplet evaporation in an 8-stage 2-D compressor by introducing an equilibrium and non-equilibrium model. The equilibrium model predicts that all the water droplets get evaporated at the end of the 3rd stage. The non-equilibrium model predicts the complete evaporation of the water droplet delays but all the droplets completely evaporate at the end of the compressor stages Khan and Wang (2013). The inlet fogging method in a wet compression process is detailly employed by using analytical equations. The reduction in the compressor's discharge air temperature is predicted Sanaye and Tahani (2010). The continuous evaporative internal cooling method in a compressor is implemented by Zheng *et al.* (2003) , in which he introduced an isentropic index for the wet compression process and also discussed the impact of the compressor exit temperature for different environmental temperatures. The water injection effect on the compressor performance is detected by implementing a simple numerical method. The computation of the wet compression process is based on droplet evaporation and mean line calculations. The entropy generation due to irreversible phase change which depends on the droplet size is bestowed. By using the mean line compressor calculations, the effects of higher mass flow rate and compression ratio have been through simple aerodynamic reasoning White and Meacock (2004). Chaker *et al.* (2004) by using the analytical and computational process studied the inlet fogging method in the inlet duct of the compressor. They explained the theory of droplet dynamics and heat transfer relating to the application referring to the inlet fogging process. A droplet heat and mass transfer model has been used for an isolated water droplet and also in forced convection conditions.

They studied the erosion in the compressor blades because of the improper drainage of the water droplet after the process completion. For droplet sizes smaller than 15-20 microns tend to follow the airstream and doesn't cause a threat to the compressor blades. Mohan *et al.* (2019) conducted an analytical and computational analysis on the wet compression process by observing the pressure, temperature, and relative humidity changes during the compression process in the system at both dry and wet conditions. They studied that for smaller droplet diameter size and higher overspray. Slower compression speed the work of the compressor has been reduced to a very reasonable level and they observed that the initial relative humidity does not affect the working fluid. Hence the effect of initial relative humidity has not been discussed in this work. Suryan *et al.* (2010) experimented to monitor the suitability of the two-fluid nozzle for the inlet fogging system by varying the air supply pressure and measuring the flow visualization, relative humidity, and temperature. Suryan *et al.* (2011) experimented by varying the length of the wind tunnel to determine the performance of the impaction pin nozzle in the inlet fogging system and found out that the impaction pin nozzle is very acceptable for the inlet fogging process.

The motion of the water droplets in each stage of an eight-stage axial subsonic compressor for the wet compression process is monitored by using numerical analysis. The water droplet diameter size of 5 microns can only reach complete evaporation upstream of the compressor outlet. A conclusion was made that fine droplet sizes are much preferable to bigger droplet sizes Luo *et al.* (2013). Bianchi and Melino (2016) developed an in house code to evaluate the performance of a gas turbine with all possible fogging strategies. Bracco *et al.* (2007) introduced a mathematical model, examined the outcomes of a wet compression process on gas turbine power plants from a thermodynamic viewpoint, and evaluated the power efficiency of a gas turbine. The results indicate a gain in power output of 14% for a 0.2% overspray. The output acquired does not change with varying ambient temperature. Gunther and Joos (2015) studied different types of fogging systems and their effect on the ambient air entering the compressors of gas turbines. The effects of inlet fog system on the performance of a typical power plant are investigated. Kim *et al.* (2011) carried out analytical modeling in which heat and mass transfer operation is settled by using the Stokes convection model. Transient behavior of evaporation rate, water droplet temperature, and droplet mass has been looked over.

Though several existing works on the wet compression process, few appear on the fundamental understanding of the wet compression process. But not an accurate study on the overspray methodology. In the present study, an analytical model of the wet compression process is considered. The analytical model used yields a suitable solution for the wet compression process. The model is used for the relevant parametric study. Unlike others, the present model found in the paper not just prioritizes the wet compression process but also applies the methodology of the overspray in the right way. In which fine water droplets will be Injected with a domain of 100% relative humidity and further study has also been done to inspect the effect of droplet diameter and compression rate with water droplets injected into the domain. As far as we know, this literature has not come through an in-depth study on the overspray methodology on the wet compression process.

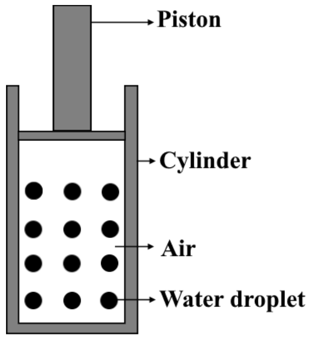

Fig. 1. Schematic for Piston cylinder with air and fine water droplets.

2. ANALYTICAL METHODOLOGY

The working fluid is modeled as fine droplets of water which is dispersed in the air. In the present analytical study, a piston-cylinder domain is considered which consists of water droplets scattered in the air as shown in Fig. . The compression process is performed by the axial motion of the piston. For simplicity, the water droplets are allowed to be spherical, monodisperse, identical droplet diameter, do not interact with each other, and uniformly dispersed inside the volume of air. The complete analytical modeling used in this paper is presented below.

2.1. Droplet Modelling

In this section, the droplet evaporation modeling is performed concerning the layer near the droplet surface area to the atmosphere. Figure 2 explains the droplet evaporation region in which the relative humidity will be maximum in the vapor layer surrounding the water droplet which occurs due to the heat and mass transfer within the liquid and gas media. The droplet evaporation is mainly due to the difference between the saturated vapor region and the atmosphere. In detail, evaporation happens when the water molecules get detached from the water droplet surface region to the saturated vapor region.

To confirm the evaporation rate of water droplets three different evaporation models have been adapted for the comparison. The models used are Maxwell (Tonini and Cossali 2012), Stefan-Fuchs's (Beji *et al*. 2019), and Spalding's model (D. B. Spalding). The evaporation rate can also be referred to by the reduction in the droplet diameter. The equations used to find the variation in the evaporation models are mentioned below,

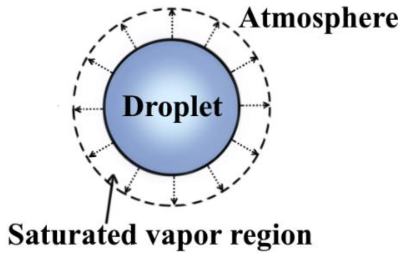

Fig. 1. Water droplet evaporation zone

The following convection model derived by Maxwell (Tonini and Cossali (2012)) is used,

$$ER = \left[\frac{(P_{sat} \cdot 18.01528)/(R \cdot T_a \cdot \rho_w)}{(T_d/T_a)} - x_{vd}\right] \cdot (4 \cdot \pi \cdot (d_r/2) \cdot DC_a \cdot \rho_w) \quad (1)$$

Thereupon $\boldsymbol{\rho_w}$ is the density of the water. $\boldsymbol{P_{d\_sat}}$ is the saturated vapor pressure formed due to the heat and mass transfer of the water droplets to the vapor vicinity region. $\boldsymbol{d_r}$ denotes the droplet diameter. $\boldsymbol{T_d}$ and $\boldsymbol{T_a}$ refer to the temperature of the droplet and the air and R denotes the specific gas constant. $\boldsymbol{x_{d\_sat}}$ denotes the specific humidity of the saturated vapor zone.

The following convection model derived by Stefen-Fuchs (Beji *et al*. (2019)) is used,

$$ER = \log\left[\frac{(1 - xv)}{1 - \frac{(P_{d\_sat} \cdot 18.01528)/(R \cdot T_a \cdot \rho_w)}{(T_d/T_a)}}\right] \cdot (4 \cdot \pi \cdot (d_r/2) \cdot \rho_w) \quad (2)$$

The Maxwell and the Stefen-Fuchs model are the two convection models used to compare the changes of the droplet diameter with time. The changes in the evaporation of the water droplet against time are observed in which the time difference for the two models is almost the same but possesses a small variation for the time taken for complete evaporation which is exposed in the inset figure in Fig. 2 .

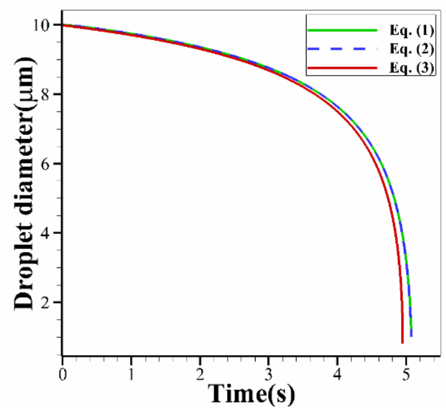

Fig. 2. Comparison of various evaporation models.

The following diffusion model derived by D. B. Spalding is used,

$$ER = -2 \cdot \pi \cdot d \cdot N_d \cdot DC_a \cdot \rho_a \cdot \ln\left(\frac{1+x}{1+x_{d\_sat}}\right) \quad (3)$$

Where N_d is the number of droplets. For diffusion models, the density of air ρ_a is also calculated. x is the specific humidity. In the comparison of the evaporation models, the Spalding diffusion model (D.B.Spalding) has been found that the droplet gets evaporated at a very quick span. For this study, a droplet diameter of 10µm and a 3% overspray is applied. In Fig. 2 it clearly shows that the droplets get evaporated at a faster rate of time for the Spalding model than the Maxwell model and Stefan Fuchs's evaporation models.

The maximum specific humidity of the given mass of air is calculated which is next used to find the specific humidity

$$\mathrm{x_{max}} = 0.622 + \frac{\mathrm{P_{sat}}}{\mathrm{P_a} - \mathrm{P_{sat}}} \quad (3)$$

Where $\mathrm{P_{sa}}$ is the saturation pressure in the droplet vapor region

$$x = RH \cdot x_{max} \cdot \frac{1 - \frac{\mathrm{P_{sat}}}{P_a}}{1 - RH\frac{\mathrm{P_{sat}}}{P_a}} \quad (4)$$

The diffusion mass coefficient of air is calculated from the relation provided by (Chaker *et al*. 2004)

$$DC_a = 2.26 \cdot 10^{-5}\left(\frac{101325}{P_a}\right)\left(\frac{T_a}{273.15}\right) \quad (5)$$

Where P_a and T_a are the pressure and temperature of the air.

The vapor mass flux of the droplet is calculated from Spalding's analysis (D.B.Spalding)

$$J = \frac{-2 \cdot DC_a \cdot \rho_a}{d}\ln\left(\frac{1+x}{1+x_{d\_sat}}\right) \quad (6)$$

The heat flux from the droplet to the ambient air is calculated by using Spalding analysis (D. B. Spalding)

$$q = -C_{pv} \cdot J \cdot \frac{(T_a - T_d)}{1 - e^{JC_{pv} \cdot d/2K_a}} \quad (7)$$

The convection heat transfer between air and droplet was calculated from

$$Q = q \cdot \Delta t \cdot \pi {d_r}^2 \quad (8)$$

The Latent heat produced is calculated by using

$$LH = \Delta M \cdot L \quad (9)$$

The specific latent heat of the droplet is given by Poling and Prausnitz (2001)

$$L = -2366.22 \cdot T_d + 3149697.516 \quad (10)$$

ΔM is the mass of the water evaporated for a time step and it can be represented as

$$\Delta M = \Delta t \cdot ER \quad (11)$$

The evaporation rate ER can be calculated using the Spalding diffusion model Eq. (3)

The updated droplet temperature can be calculated by using:

$$T_{d(t+\Delta t)} = T_{d(t)} + \frac{Q - LH}{M_{dt} \cdot c_{p,dt}} \quad (12)$$

2.2. Model of the Wet Compression Process

The compression process of the liquid gas media is been carried out by a simple piston-cylinder system. For a cylinder the change in volume ΔV for a time step is calculated using:

$$\Delta V = \frac{\pi}{4} \cdot D^2 \cdot cs \cdot \Delta t \quad (13)$$

The main concern of this work is to get a deep understanding of the transients involved in the evaporation of water droplets. For this to be studied, a simple piston – cylinder system has been considered. In this setup, the wet compression process has been incorporated by dispersing water droplets inside the air-filled cylinder and allowing the piston movement to happen. Here, spherical droplets with the same diameter are being placed inside the cylinder filled with air which is in saturated condition i.e., RH = 100%. Now at a particular compression speed when the piston starts to move, the temperature inside the system increases, thereby bringing in the evaporation of the water droplets. The total time and the time interval for the piston motion are fixed along with the initial conditions. For each time interval, the calculation is being done along with a time increment, until the time equals the total time. The steps occurring in the calculation have been shown in a proper order using a flow chart in Fig. 4 and the process has been elaborated using formulae.

At time t = 0 s, the air-filled cylinder is taken with initial volume, pressure, and temperature to be V_0, P_0 , and T_0 respectively. The air is considered to be ideal gas and hence the initial mass of gas calculation is done as follows:

$$M_0 = \frac{P_0 \cdot V_0}{R_0 \cdot T_0} \quad (14)$$

Then the mass calculation for the liquid is done using the diameter of the dispersed droplets:

$$M_d = \frac{\pi}{6} \cdot {d_r}^3 \cdot N_d \cdot \rho_d \quad (15)$$

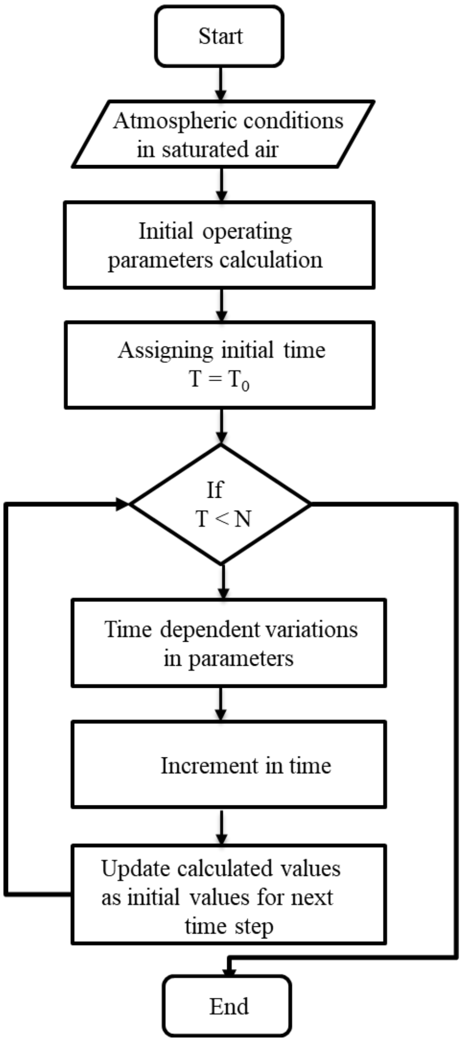

Fig. 3. Flowchart for the present analytical calculation.

Following this Antoine's equation is applied to determine the saturated vapor pressure of both air and the droplet individually using temperatures T_a and T_d respectively:

$$\log_{10} P_{sa,sd} = A - \frac{B}{C + T_{a,d}} \tag{16}$$

The partial vapor pressure for air is then calculated:

$$P_{vap} = x \cdot \frac{P_a}{0.622 + x} \tag{17}$$

Then the mass of vapor and specific humidity of air are updated with values from the following equations

$$M_{v_{t+\Delta t}} = M_{v_t} + \Delta t \tag{18}$$

$$x_{t+\Delta t} = \frac{M_{v_t+\Delta t}}{M_{da}} \tag{19}$$

The Decremented value of the volume is then calculated by using:

$$V_{a_{t+\Delta t}} = V_t - \Delta V \tag{20}$$

The ideal gas equation for the updated pressure is calculated by using

$$P_{a_{t+\Delta t}} = \frac{M_a \cdot R_a \cdot T_a}{V_a} \tag{21}$$

The temperature raise occurring due to the compression work done by the piston given as PΔV can be found using the energy equation:

$$T_{a_{t+\Delta t}} = T_{a_t} + \frac{P \cdot \Delta V - Q}{M_t \cdot c_{p,at}} \tag{22}$$

The efficiency of the wet compression process is been calculated by using the relation:

$$\eta_{wet} = \frac{W_{dry} - W_{wet}}{W_{dry}} \times 100\% \tag{23}$$

3. MODEL VALIDATION

The validation of the wet compression model is evaluated by using D^2 - law of evaporation. This is also a quasi-steady model in which it demonstrates, at the time of the gasification process the surface area of the droplet is represented by the droplet squared diameter, which decreases linearly with its lifetime. The D^2 – law of evaporation is referred from Ragab and Wang (2016).

$$d_{p_0}^2 - d_p^2 = \lambda \cdot t \tag{24}$$

Where λ represents the droplet evaporation constant.

Figure 4. describes the comparison of the experimental results by (Ranz 1952) and the analytical model with the single droplet. For the validation a droplet with a diameter of 1.1mm, initial droplet temperature of 282K, and initial air temperature of 282K. When the evaporation begins, once the droplet is placed, the water droplet tends to lose the water as it is considered to equilibrium the variation in diameter becomes linear.

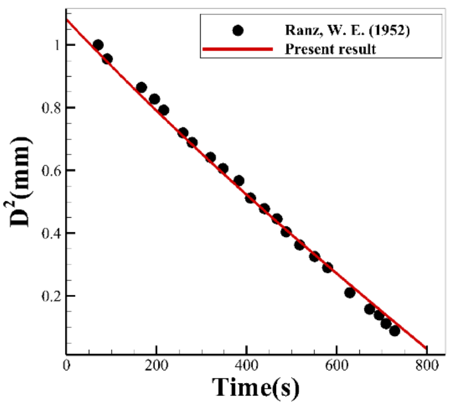

Fig. 4. Comparison of the analytical results with experimental ones.

And also, as the droplet temperature is higher than the ambient temperature, the droplet tends to evaporate at a faster rate. In this judgment, it can be observed that the droplet diameter declines linearly with time and reaches zero. This unveils a good match with the experimental one.

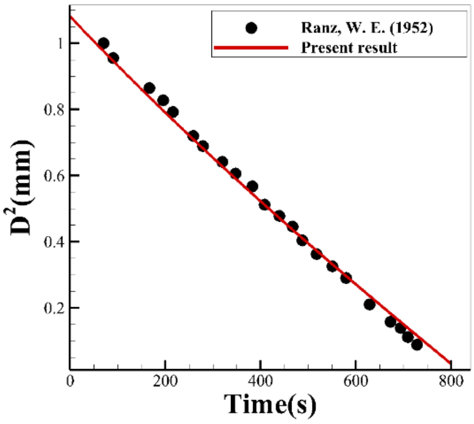

Fig. 5. Comparison of the analytical results with experimental ones.

4. CALCULATION CONDITIONS

To verify the procedure and the results of the wet compression process the analytical results are shown below. A piston and cylinder with a dimension of about 3mm in diameter and 3mm in height are chosen. The calculations are carried out at 101325 Pa pressure range. The efficiency of the wet compression process and thermodynamic curves are plotted as follows, the thermodynamic curves obtained are for the Overspray effect, Droplet diameter effect, and effects for various compression rates. In most of the practical cases of the wet compression process, the nozzle spray characterized by diameter values of less than 10 and 15 µm has been used. But in a multistage compressor, the droplet sizes should be chosen such that the droplets should not be completely evaporated before the entire compression process. So, higher droplet diameters seem to be efficient for compressors with more stages. Luo *et al*. (2013) have considered a 5 µm droplet because they can follow the airflow better. Also, though aerodynamic breakup occurs due to impaction on the surface is small for 5 µm droplet. But in the present work, thermodynamic heating occurring due to compression is the only phenomenon causing droplet evaporation. Considering all these aspects for this investigation, the droplet diameters 1µm, 5 µm, 10 µm, 20 µm, and 30 µm have been chosen. But when the injected water does not completely evaporate during compression, it may lead to erosion on the trailing edge of the compressor blades. Sanaye and Tahani (2010) has shown that 3% overspray is good enough for an efficient compression process. But Mohan *et al*. (2019) has shown that compression rate affects overspray percent. So 1%, 3%, 6%, 10%, and 15% and 20% are the taken oversprays. For a typical compressor, the compression ratio for a dry air case will be ranging from 1.2 to 4 with losses. The maximum efficiency that can be accomplished for a typical compressor varies from 70 – 90%. For an isentropic system, the compression ratio can range from 8 to 25. In addition, Mohan *et al*. (2019) has compared different compression rates to show the variations accordingly. Hence 3, 35, and 353mm^3/s are the fixed compression rates.

5. RESULTS AND DISCUSSION

5.1. Effect of Overspray

Overspray can be interpreted as the mass of water beyond the quantity required to saturate a quantity of air i.e when relative humidity reaches 100%. The mass of water to be injected for a particular overspray can be calculated using,

$$M_w = M_v + (OS \cdot M_a) \tag{25}$$

So far the overspray has been defined in different ways. Some have initially considered saturated air (RH=100%) taken at atmospheric conditions, sprayed water in it, and then allowed water to get into equilibrium with the air which causes variations in the relative humidity of the air, by this as the initial condition the wet compression process has been carried out, which shows similarity with the inlet fogging system. In the present work, the equilibrium is considered to have attained when the water is injected and so without any change in the initial conditions provided the wet compression process has been done. In this literature, the effect of overspray in the wet compression process has been explained thoroughly with the variations in droplet diameter, temperature, pressure ratio, relative humidity, and compression rate for different conditions.

For this analysis a 10µm droplet, overspray variations of about 1%, 3%, 6%, 10%, 15%, 20% and with a 353mm^3/s compression rate are considered. The initial temperature of air and droplet is maintained at 300K. When the droplet size is very small, the evaporation will be fast which causes the droplets to evaporate before the entire compression process. So for the chosen domain, the smallest droplet that could stay for the entire compression process is considered for this analysis. Also, slower compression can be effective but is also time-consuming. So within a short span, efficient overspray is found by taking a faster compression rate.

Figure 6 and Fig. 7 presents the variation in pressure and temperature. In those two plots it obvious that for higher overspray the pressure and temperature achieved is lower. For a higher overspray, the vapor pressure increases, hence for a particular compression volume the temperature and pressure drop will be higher. But for 1% overspray, it is observed that the droplet diameter comes to a negligible size before the entire compression process gets over. The complete evaporation of water droplet Is shown in Fig. 9. In Fig. 8 for a lower overspray percentage the relative humidity drops rapidly. The

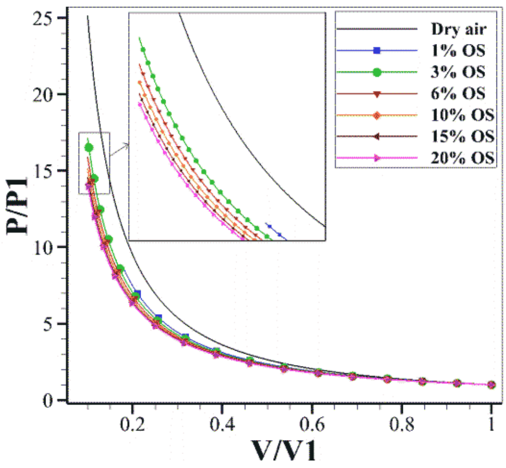

Fig. 6. Effect of overspray: P–V curve (Initial droplet diameter – 10 µm, initial air, and initial droplet temperature – 300 K, compression rate – 353mm^3/s, initial RH – 100%).

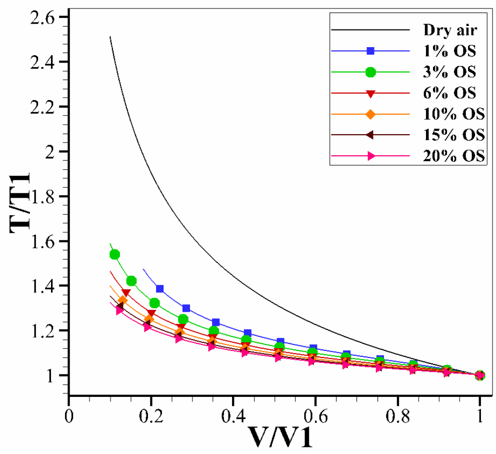

Fig. 7. Effect of overspray: T–V curve (Initial droplet diameter – 10 µm, initial air, and initial droplet temperature – 300 K, compression rate – 353mm^3/s, initial RH – 100%).

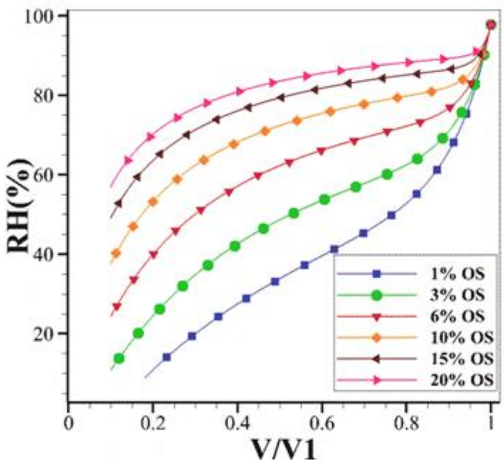

Fig. 8. Effect of overspray: RHV curve (Initial droplet diameter – 10 µm, initial air, and initial droplet temperature – 300 K, compression rate – 353mm^3/s, initial RH – 100%).

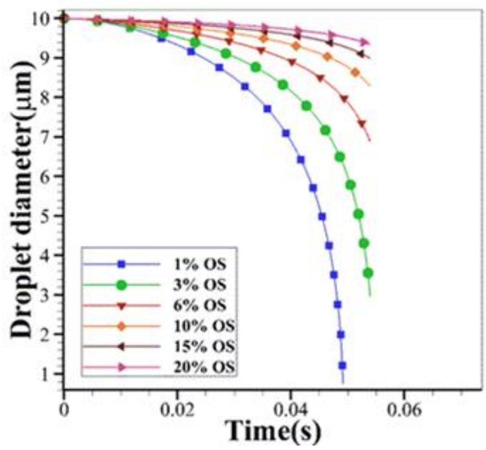

Fig. 9. Effect of overspray: Variation of droplet diameter (Initial droplet diameter – 10 µm, initial air, and initial droplet temperature – 300 K, compression rate – 353mm^3/s, initial RH – 100%).

mass of the water for a lower overspray will be less. During the compression process, the saturation vapor pressure increase more at the same time the vapor pressure is suppressed to a larger extent. Which shows the higher evaporation rate achieved.

5.2. Effect of the Diameter of the Water Droplet

For this analysis, an overspray of 3% with a 353mm^3/s compression rate and droplet diameter of 1,5,10,20, and 30 µm are considered. Sanaye and Tahani (2010) has explained that 3% overspray brings in an efficient compression. Also, 3% overspray does not evaporate totally with smaller droplets or remain more with larger droplets at end of compression. Comparatively, it gives better performance. Hence 3% overspray has been preferred for this study. At the beginning of the process air and droplet temperature is kept constant at 300K. The starting relative humidity is 100% at the start of the compression process. The difference in the pressure and temperature variation is exhibite in Fig. 10 and Fig. 11. For a smaller droplet diameter, the pressure drop is higher and the temperature rise is not dominant when compared with the bigger droplet diameter. As the evaporation rate is a function of vapor mass flux, the smaller droplet diameter posses lesser surface area which enhances the higher rate of heat absorption by the smaller droplets thereby reducing the temperature and pressure.Further, the 1µm droplet diameter size is shown to explain the effect by the negligibly small size droplet diameter. Which indicated the water droplet diameter undergoes complete evaporation before the entire compression process gets completed.In Fig. 12 at the initial start of the compression process, a progressive amount of heat

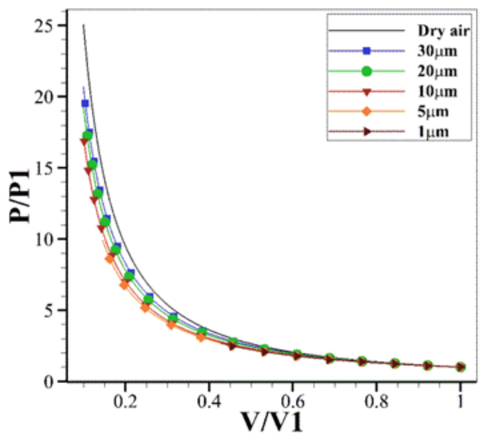

Fig. 10. Effect of the Diameter of Water Droplet: P–V curve (Overspray – 3%, initial air, and initial droplet temperature – 300 K, compression rate – 353mm^3/s, initial RH – 100%).

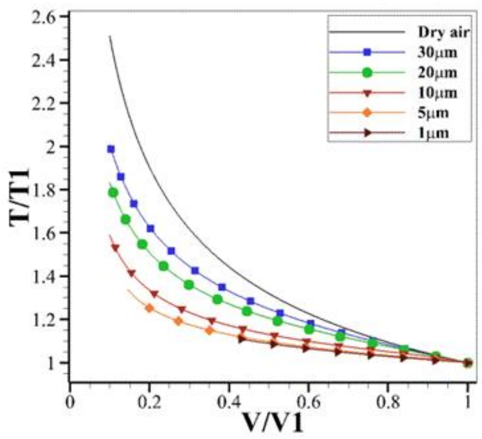

Fig. 11. Effect of the Diameter of Water Droplet: T–V curve (Overspray – 3%, initial air, and initial droplet temperature – 300 K, compression rate – 353mm^3/s, initial RH – 100%).

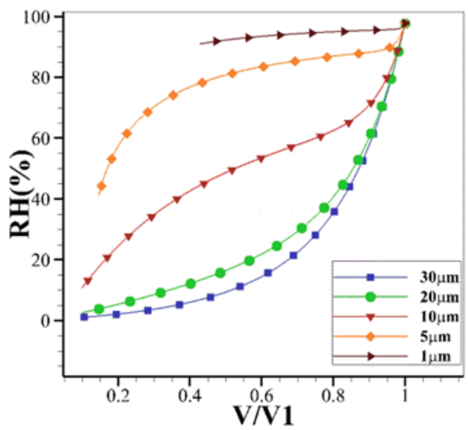

Fig. 12. Effect of the Diameter of Water Droplet: RHV curve (Overspray – 3%, initial air, and initial droplet temperature – 300 K, compression rate – 353mm^3/s, initial RH – 100%).

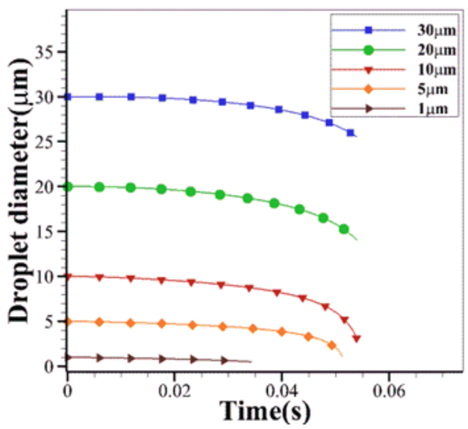

Fig. 13. Effect of the Diameter of Water Droplet: Variation of droplet diameter (Overspray – 3%, initial air, and initial droplet temperature – 300 K, compression rate – 353mm^3/s, initial RH – 100%).

has been supplied, as a result of which droplets get vaporized.

This causes the saturated vapor pressure to develop in the system which drives to a decrease in actual vapor pressure. Hence the relative humidity decreases gradually. Figure 13 displays the transitory behavior of the droplet diameters with time. Larger droplets demand a long time to evaporate but the larger ones will enhance the cooling effect in later compressor stages in which the smaller droplets will not be available because they would be complete in their early stages. For the smaller droplets the increase in evaporation rate high when related to a larger droplet. The low surface area of the smaller droplet is the reason for the higher evaporation rate.

5.3. Effect of the compression rate

For this analysis, an overspray of 3% with a droplet diameter of 10μm and compression rate of 3, 35, and 353mm^3/s is considered. The initial air and droplet temperature is kept constant at 300K. The relative humidity is 100% at the start of the compression process. When considering dry compression on changing the compression rate, for the same volume the temperature rise at the end is different. Now on including overspray, the effect again changes throughout the process.

It is obvious from Fig. 14 and Fig. 15 for a slower compression rate the pressure and temperature achieved are seen to have a huge drop in pressure and temperature compared to a higher compression rate.

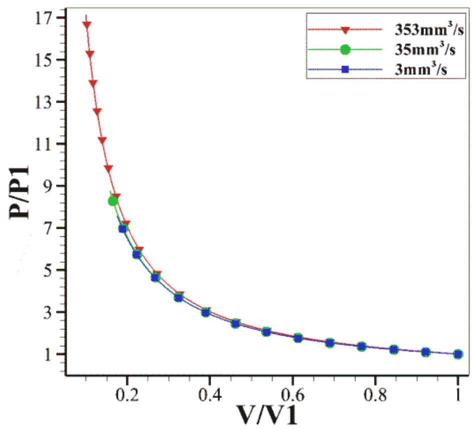

Fig. 14. Effect of compression rate: P–V curve (Overspray – 3%, initial droplet diameter –10 µm, initial air, and initial droplet temperature – 300 K, initial RH – 100%).

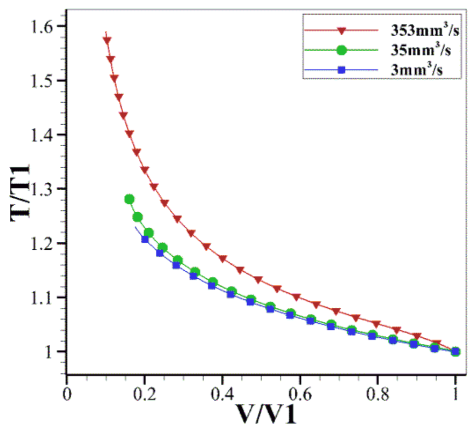

Fig. 15. Effect of compression rate: T–V curve (Overspray – 3%, initial droplet diameter –10 µm, initial air, and initial droplet temperature – 300 K, initial RH – 100%).

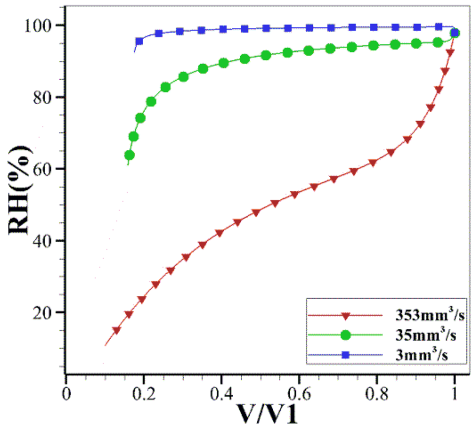

Fig. 16. Effect of compression rate: RHV curve (Overspray – 3%, initial droplet diameter –10 µm, initial air, and initial droplet temperature – 300 K, initial RH – 100%).

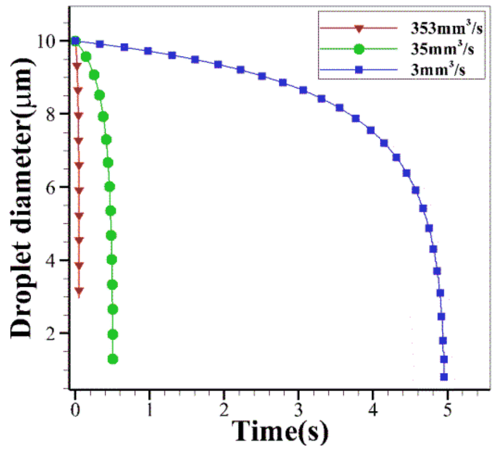

Fig. 17. Effect of compression rate: Variation of droplet diameter (Overspray – 3%, initial droplet diameter –10 µm, initial air, and initial droplet temperature – 300 K, initial RH – 100%).

This is due to the excess time available for the evaporation of the water

droplets injected. Moreover, it can be explained as the water droplet have an enormous amount of time to absorb the heat from the air produces during the compression work. Figure 16 shows the relative humidity variation for different compression rates. The air-water mixture is influenced by the compression rates. For a lower compression rate, the evaporation time will be more leading, which drives to a higher evaporation rate. The relative humidity decreases at a slower rate when the compression rate is low. The relative humidity decreases at a faster rate when the compression rate is high. This shows the availability time for the evaporation process is less. The transient behavior of the droplet diameter variation with time is shown in Fig. 17. For a higher compression rate, the time available for the evaporation of the water droplets will be low hence it can be noticed that the size reduction in the droplet diameter size is less. On the other hand for the slower compression rate, the available time required for the complete evaporation is huge, as a result, complete evaporation of the droplet can be achieved. When the time available for the complete evaporation for the water droplet is enhanced the heat transfer between the water droplet and the air will be immense which thrives for a higher evaporation rate.

5.4. Efficiency of the wet compression process

The efficiency of the wet compression process is been calculated by using Eq. (24). Figure 18, Fig. 19, and Fig. 20 reveal the wet compression efficiency values for all the parametric studies conducted on the current work. It can be seen that for the highest overspray, smallest droplet diameter, and slower compression rate achieves higher efficiency and it shows the work drawn from the compressor is less.

The smaller compression rate allows the droplet diameter to evaporate completely, hence comparatively with the other compression rates the

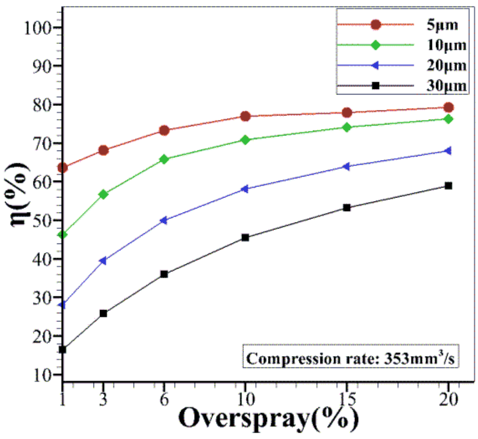

Fig. 18. Efficiency of the wet compression process: (compression rate 353mm^3/s, initial air, and initial droplet temperature – 300 K, initial RH – 100%).

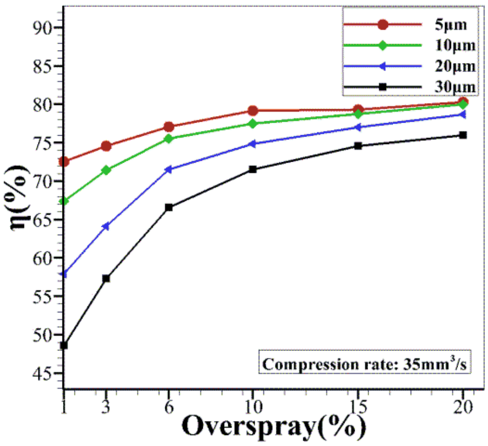

Fig. 19. Efficiency of the wet compression process: (compression rate 35mm^3/s, initial air, and initial droplet temperature – 300 K, initial RH – 100%).

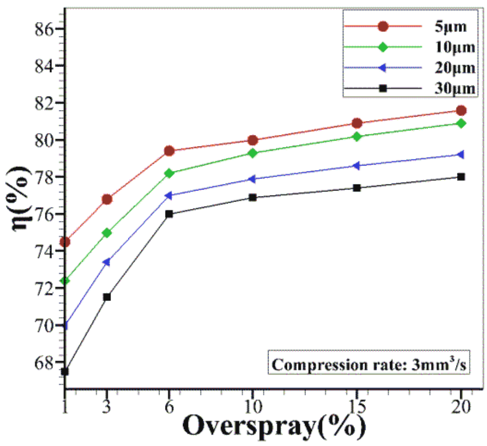

Fig. 20. Efficiency of the wet compression process: (compression rate 3mm^3/s, initial air, and initial droplet temperature – 300 K, initial RH – 100%).

smaller compression shows a higher efficiency. The changes in the efficiency for 5µm droplet diameter are higher and it doesn't show a larger deviation when compared with the 30µm droplet diameter, which implies the evaporation rate for a smaller droplet diameter is higher even with the changes in overspray percentages. Hence energy has been saved. The higher wet compression efficiency indicates the huge amount of compressor work savings. Thereby, the pressure and temperature drop are higher for less compressor work.

6. CONCLUSION

The performance of the wet compression process using an analytical model by considering a piston-cylinder system and by spreading fine droplets of water in the air is studied. The validation of the model has done by using the D^2 - law of evaporation with the experimental result Fig. 4. Parametric evaluations have been done to detect the effect of the percentage of overspray, the effect of the droplet diameter, and the effect of different compression rate. The following statements are made from the obtained analytical results;

- The overspray methodology implemented in the wet compression process at saturated air condition (RH-100%) provides a reduced compressor work by reducing the temperature and pressure than the work done in the dry air compression.
- The smaller compression rate accelerates the evaporation of the water droplet thus increasing the efficiency of the compression process.
- Droplets with small diameters have a huge impact on the compressor work whereas the higher droplet diameter has a reduced

evaporation rate which depends purely on the surface area of the water droplet.

- As Sanaye and Tahani (2010) mentioned 3% overspray seems to be much more efficient than the other overspray cases which is very evident in this work.

Although increasing the overspray percentage will decrease the compressor work which is achieved by reducing the temperature of the system. Increasing the overspray percentage is not very appreciable, because the unevaporated droplets get to stay inside the system even after the end of the compression process which will lead to the corrosion of the compressor blades. By using the obtained results, it can be utilized as a pattern for a more solid knowledge of a wet compression process in a gas turbine system.

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