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Research Paper

Optimization of wet compression effect on the performance of V94.2 gas turbine

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HIGHLIGHTS

- Wet Compression analytical method for cooling compressor inlet air is modeled.
- Flow and work compatibility called matching component leads to determine work line.
- Droplet diameter, temperature and overspray effects have been investigated.
- Cuckoo search can find the best condition with reliable values in Gas Turbine Cycle.
- The best point will be selected between surge and choke margin in compressor map.

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ABSTRACT

Wet compression has been widely used in recent years for power augmentation and gas turbine efficiency improvement. In order to explore this issue, the paper first focuses on the effects of wet compression, an analytical method based on droplet evaporation. Matching compressor-turbine or typically matching component has been added to this model for the compatibility of mass flow, rotational speed and power. Since this essay advances the idea of optimization, one of the metaheuristic algorithms Cuckoo Search (CS) has been considered. Three variables including droplet diameter, amount of overspray and droplet size have been taken into account. The objective function is turbine output work where compressor will work out of surge and choke domain. The numerical results indicate degradation in compressor inlet air temperature and noticeable power increments.

1. Introduction

Over the years, the application of wet compression for power augmentation of gas turbines has become popular and it has a history since 1940′s. This article has covered analytical and physical process of wet compression with considering prediction equation for the amount of actual increased power output and investigation of compressor operating work line by dry compression matching. In order to achieve new goal in wet compression optimization, cuckoo search [19] algorithm has been used. Thermodynamic wet compression model was proposed by Hill [1] and then it was developed by Zheng et al [2,3]. The effectiveness of this cooling is more obvious at warmer weather and lower relative humidity. Wet compression causes adiabatic compression to move into isothermal compression state. Nowadays due to economical factors, more attention has been devoted to wet compression for power output increment and No$_x$ decrement. In 2006 Khan and Wang developed a new model for burning low calorific value (LCV) fuels by using wet compression for a gas turbine system [4]. Some efforts have been done in order to investigate the evaporation time for droplets. In 2006 Abdelwahab [5] applied wet compression in a centrifugal compressor to find the injection rate and droplet radii effect on the pressure ratio in which compressor each stage can reach. Bhargava and Meher-Homji [6] investigated the performance parameters like turbine temperature, compressor inlet temperature, heat rate and fuel flow rate. Sanaye studied the effect of wet compression on gas turbine performance and compared their findings with Fluent software [7]. The effects of overspray on the Gas turbine blades have been studied by Matz [8]. Some other works without claim of completeness are mentioned in the paper. Day et al. worked two-phase flow in a compressor [9]. Droplet behavior in the compressor was investigated by White and Meacock numerically [10]. In order to get more details in droplet evaporation, it can be referred to works done by Russo et al [11]. Experimental works on wet compression has been done by Ober and Joos [12]. For considering the aerodynamic behavior of a compressor cascade in droplet laden flow,

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Nomenclature

C_x	air axial velocity
T_a	air temperature (K)
U	blade velocity (m/s)
Γ	coefficient of mass diffusion
K	constant coefficient
h	convection heat transfer coefficient
CE	cooling efficiency
N_c	corrected speed
$\dot{m}_c$	corrected mass flow rate
ρ	density (Kg/m^3)
T_d	droplet temperature (K)
D	droplet diameter (μm)
ELR	egg laying radius
h_{fg}	evaporation enthalpy (J/Kg)
φ	flow coefficient
X	habitat
L_v	latent heat of vaporization of water
ψ	load coefficient
M	molecular weight
m_d	mass of droplet
ϕ_{evap}	mass transfer flux
Nu	Nusselt number
OS	over spray
η_p	polytrophic efficiency
RH	relative humidity
α	rotor angle
P_s	saturated pressure
Sf	shape factor
Sh	Sherwood number
β	stator angle
S_d	the droplet and air contact Surface area
t	time
TIT	turbine inlet temperature
R	universal gas constant 8.314 (J/mol·K)
P_v	vapor pressure

there are several other references about wet compression using numerical, experimental and analytical approaches that are out of the scope of the paper and therefore they are not mentioned here. In this paper up to 3% over spray which is the ratio of water injection mass flow rate to the air mass flow rate in duct's inlet has been studied. Two key points are the matching compressor-turbine and evaluating the best condition for injection. For this purpose, one of the new metaheuristic algorithms Cuckoo Search (CS) has been used. For wet compression modeling, parameters like ϕ, ψ, Nc and pressure ratio at each stage of compressor have been calculated analytically. Extracting compressor work line and compressor characteristics map are two novel approaches done across wet compression. Other investigations are precisely mentioned as follow:

- Calculating the compressor outlet temperature and pressure.
- Evaluating the new characteristic map in both compressor and turbine and obtaining the corrected mass in compressor map.
- Calculating turbine output power, network power and gas turbine efficiency.
- Optimization and finding the optimum overspray.

In this paper the cuckoo search algorithm has been used. For this purpose, objective function has been considered motor output work and three goal variables including droplet diameter, droplet temperature and water injection for single objective optimization has been selected. The acceptable solution is based on surge constraint extracted from compressor dry map.

2. Analysis methodology

2.1. Droplet evaporating model

The vapor penetration occurs from the layer near droplet surface to the ambient air with relative humidity equal to 100% [13]. The concentration difference between the layer and ambient air leads to evaporation [7]. Since the utilized model is based on semi-one-dimension approach, response time refers to the time needed for droplets to reach the air flow velocity has been considered. Some validated assumptions by Chaker et al [14] have been used in the modeling.

1. It is good to study the droplets individually and then extend it to the interface between droplets and the air.
2. Radiation heat transfer has been neglected in order to avoid equation complexity.

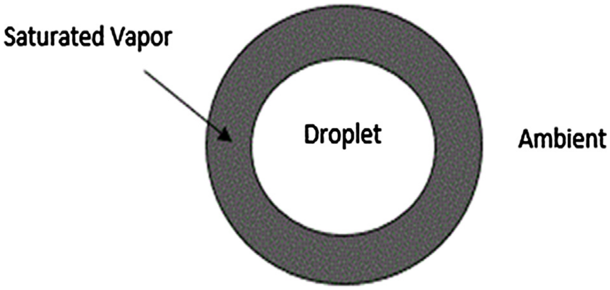

Fig. 1. Droplet evaporation modeling [13].

3. Droplet has been assumed spherical.

Computations were carried out in small time intervals by using the following relations. This trend will continue until the evaporation of all droplets at the end of the duct. The main phenomenon occurs by injection is convection and diffusion at the interface of water droplet and air in the compressor duct. Therefore, the thermal equilibrium will be:

$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_{lat} \tag{1}$$

The rates transferred between droplet and the air is calculated from:

$$\dot{Q}_{conv} = h_{conv} \times S_d \times (T_a - T_d) \tag{2}$$

h_{conv} is the thermal convective coefficient and is derived from the Nusselt number and for natural convection the Nusselt number is function of the thermal Grashof and Prandtl Number which is given by:

$$Nu = 2 + 0.6Gr_t^{0.25} \times Pr^{0.33} \tag{3}$$

$$\dot{Q}_{lat} = \frac{\Delta m_d \cdot L_v}{\Delta t} \tag{4}$$

$$L_v = 1000(2498 - 2.413 \times T_d) \tag{5}$$

$$\Delta m_d = -\Delta t \times S_d \times \phi_{evap} \tag{6}$$

ϕ_{evap} is the mass flux. By considering all conditions and assuming the air near the droplet as a perfect gas finally the evaporative flux may be written as:

$$\phi_{evap} = \frac{M \cdot Sh \cdot \Gamma}{R \cdot D} \cdot \left(\frac{P_s}{T_d} - \frac{P_v}{T_a}\right) \tag{7}$$

The energy stored in a droplet during time interval will be: