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Numerical Investigation of the Flow Characteristics inside the Scrubber Unit

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***Abstract*—**Wet scrubbers have found widespread use in cleaning contaminated gas streams because of their ability to remove particulates and based on the applications of scrubbing of marine engine exhaust gases by spraying sea-water. In order to examine the flow characteristics inside the scrubber, the model is designated with flow properties of hot air and water sprayer. The flow dynamics of evaporation of hot air by the injection of water droplets is the key factor considered in this paper. The flow behavior inside the scrubber was investigated from the previous works and to sum up the evaporation rate with respect to the concentration of water droplets are predicted to bring out the competent modelling. The numerical analysis using CFD facilitates in understanding the problem better and empathies the behavior of the model over its entire operating envelope.

***Keywords*—**Concentration of water droplets, Evaporation rate, Scrubber, Water sprayer.

I. Introduction

NEW technologies have been adopted by the marine industry to control the air emission from ship. Measures to reduce the sulfur oxide (SO_x) emissions inherent with the relatively high sulfur content of marine fuels. The motivation of the present study emanates to cool down the upcoming hot stream air by spraying water droplets. In actual flow problem, to control the emission of SO_2 in scrubber, the temperature of the flue gases should be dropped down by spraying sea-water droplets. To do so, encountering the effective mixing of hot gas and water droplets should be adopted, which is the primal importance in realizing the actual flow problem.

Yelebe et al. [1] described from the industrial point of view that the construction of scrubber system is simple and showed that the system requires less initial cost as compared to the other conventional systems. Secondly, Danzomo et al. [2] performed the numerical simulations using CFD to study the flow characteristics of a wet scrubber. This report fails to examine the evaporation rate which occurs due to the impact of water droplets over the hot gas which was predicted in this paper. Bade et al. [3] observed the hollow cone spray to measure the spray shape, size and distribution characteristics of various incident angles. On the other hand, Goniva et al. [4] carried out the simulation using DPM (Discrete Phase Model) method which was done with droplet particle where the representative droplets are traced in lagrangian frame of reference.

To put it briefly, the hydrodynamic study of the wet scrubber system based on liquid-to-gas-ratio, inlet and outlet liquid flow rates was investigated by Manyele [5]. Subsequently, the brief history about the flue gas desulfurization process and the current situations with respect to the development trends in technology were presented by Jamil et al. [6]. However, an unsteady numerical approach involving desulphurization process of exhaust gas in a wet scrubbing system using seawater were obtained by Caiazzo et al. [7]. To sum up, the grouping and trapping of evaporating droplets were probed by Katoshevski et al. [8].

The main objective of the problem lies in examining the flow physics inside the scrubber to explore the design of the system investigating the thermodynamic parameters, evaporation and concentration of the spray water droplets on the subject of liquid to gas ratio. The magnitude of evaporation rate is the most significant parameter serves to evaluate the performance of the system. With respect to the evaporation rate, the concentrations of water droplets are influenced explaining the purpose and function of the wet scrubber system.

II. Numerical Methodology

A. Governing Equations

The appropriate governing equations involving three dimensional steady state-unsteady particle tracking, turbulent flow, and compressible, reacting, turbulent kinetic energy with dissipation rate was employed in the scrubber design. The numerical methodology has been accomplished by the commercial software FLUENT 14.0.

$$\frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_k}{\partial x_k} - \delta_{ij}\right) - \rho\overline{u_i u_j}\right) - \frac{\partial p}{\partial x_i} + F \tag{2}$$

$$\frac{\partial}{\partial x_i}(\rho u_i h) = -\frac{\partial}{\partial x_i}\left(k + k_t\right)\frac{\partial T}{\partial x_i} - \frac{\partial}{\partial x_i}\Sigma h_j J_j + \tau_{ik}\frac{\partial u_i}{\partial x_k} \tag{3}$$

The velocities are represented in tensor form with the notations i, j and k as u_i, u_j and u_k along directions x_i, x_j and x_k and ρ is the density of air. In momentum equation, p denotes

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pressure, μ represents the coefficient of viscosity, F is the body force due to interaction of the discrete phase with the continuous phase and $\rho u_i u_j$ is the component of Reynolds stress tensor. In energy equation, T represents temperature, τ_{ik} indicates the shear stress tensor, k and k_t are the components of thermal conductivity and turbulent thermal conductivity. The enthalpy for ideal gases is denoted as h and is written as a summation of mass fractions times species enthalpy,

$$h = \sum Y_j h_j \tag{4}$$

Species Transport Equation

$$\frac{\partial}{\partial x_i}(\rho u_i Y_i) = -\frac{\partial}{\partial x_i}(J_i) + S_i \tag{5}$$

S_i is a source from the liquid droplet phase that is activated when evaporation occurs. Species transport due to diffusion is calculated by the diffusion flux J_i. For turbulent flows,

$$J_i = -\frac{\partial}{\partial x_i} Y_i \left(\rho D_{i,m} + \frac{\mu_t}{Sc_t} \right) \tag{6}$$

where $D_{i,m}$ is the diffusion coefficient of the i^{th} species in the mixture and Y_i indicates the count of the species. μ_t is the turbulent dynamic viscosity, D_t is the turbulent diffusivity, τ_t is the turbulent shear stress factor and Sc_t is the turbulent Schmidt number.

$$Sc_t = \frac{\mu_t}{\rho D_t} \tag{7}$$

In turbulence modelling, the simulation of two phase flow in wet scrubber is conducted in steady state.

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{8}$$

$$\frac{\partial}{\partial x_i}(\rho u_i k) = \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + G_k - \rho\varepsilon \tag{9}$$

$$\frac{\partial}{\partial x_i}(\rho u_i \varepsilon) = \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + C_{1\varepsilon} G_k \frac{\varepsilon}{k} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \tag{10}$$

In turbulence model, the subscript t represents turbulence. The k-ϵ equation contains the term G_k which indicates the production of turbulent kinetic energy.

$$G_k = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_i} \tag{11}$$

The model constants are $C_{1\epsilon}$, $C_{2\epsilon}$, C_μ, σ_k and σ_ϵ have the default values.

$$C_{1\varepsilon} = 1.44,\ C_{2\varepsilon} = 1.92,\ C_\mu = 0.09,\ \sigma_k = 1.0,\ \sigma_\varepsilon = 1.3$$

For high-Weber-number flows in spray model, wave breakup model is considered such that the breakup of the droplets to be induced by the relative velocity between the gas and liquid phases. The model assumes that the time of breakup and the resulting droplet size are fastest-growing.

$$\frac{\partial u_p}{\partial t} = F_D \left(u - u_p \right) + \frac{g_z \left(\rho_p - \rho \right)}{\rho_p} \tag{12}$$

The distribution and reduction of water droplet size due to evaporation is given by rosin-rammler property. The additional force which includes thermophoretic force and Saffman Lift force are neglected due to increase in drag on the model.

$$F_D = \frac{18\mu}{\rho_p d_p^2} \frac{C_D \operatorname{Re}}{24} \tag{13}$$

In spray model, the subscript p indicates droplet where d_p, u_p, ρ_p, τ_p indicates diameter, velocity, density of the droplet and droplet breakup time. F_D indicates the drag force term, g_z represents the gravity in z-direction, C_D refers to coefficient of drag and Re primarily notes the Reynolds number.

$$\operatorname{Re} = \frac{\rho d_p \left| u_p - u \right|}{\mu} \tag{14}$$

The unsteady trajectory calculation by discrete phase model is given by the droplet velocity u_p as,

$$\frac{\partial u_p}{\partial t} = \frac{\left(u - u_p \right)}{\tau_p} + a \tag{15}$$

Referring (15), a is the acceleration term due to the force and for the wave breakup model, the child drop size is denoted as r and u_r is the velocity of child drop size.

$$a = \frac{3}{8} C_D \frac{\rho u_r^2}{\rho_p r} \tag{16}$$

$$r = B_0 \Lambda \tag{17}$$

The droplet breakup time is described as,

$$\tau_p = \frac{3.726 B_1 a}{\Lambda \Omega} \tag{18}$$

For wave breakup model constants, B_0=0.61(default), B_1=15~60 (Larger the value for B_1 will delay the breakup). The wavelength of unstable particle wave and wave number are given by,

$$\Lambda = 2\Pi \sqrt{\frac{3\sigma}{a\rho_p}} \tag{19}$$

$$\Omega = \sqrt{\frac{2a}{3}\left(\frac{a\rho_p}{3\sigma} \right)^{1/4}} \tag{20}$$

Δt governs the accuracy and speed of calculation where Δt=(Δt)*/λ. The particle is tracked by the current cell through Δt where σ indicates surface tension of particle. The estimated transit time is defined as (Δt)*. λ is the Step Length Factor. As defined by equation, λ is inversely proportional to the integration time step and is roughly equivalent to the number of time steps required to traverse the current continuous phase control volume. The default value for the step length factor is 5. For the particle velocity at the new location $u_p^{(n+1)}$ we get,

$$u_p^{n+1} = u^n + e^{-\frac{\Delta t}{\tau_p}}\left(u_p^n - u_n\right) - a\tau_p\left(e^{-\frac{\Delta t}{\tau_p}} - 1\right) \tag{21}$$

The new location $x_p^{(n+1)}$ can be computed from the similar relationship as,

$$x_p^{n+1} = x_p^n + \tau_p\left[\left(1 - e^{-\frac{\Delta t}{\tau_p}}\right)\times\left(u_p^n - u_n - a\tau_p\right)\right] + \Delta t\left(u^n + a\tau_p\right) \tag{22}$$

In these equations u_p^n and u^n represent particle velocities and fluid velocities at the old location. The analytic discretization scheme is applied in (21) and (22).

TABLE I
WET SCRUBBER BOUNDARY CONDITION

Index	Boundary condition	Data
Inlet - Air	Mass flow rate	3.05556kg/s
	Temperature	500K
Outlet	Pressure	101.325kPa
Injection - Water droplet	Velocity	60m/s
	Temperature	300K
	Type	Hollow cone
Droplet Injection	3 sections* 9 inlets = 27 injection ports	
Top section	Hollow cone angle	120°
	Droplet diameter	0.1mm
Mid and Low section	Hollow cone angle	80°
	Droplet diameter	0.5mm
Wall	No slip, adiabatic	

B. CFD Modelling

The wet scrubber has been designed using CATIA V5R19. The boundary conditions of wet scrubber model are defined in the Table I. Fig. 1 shows the wet scrubber geometry defining the boundary conditions. The upcoming hot stream air from the inlet is simulated tangentially over the surface of scrubber model to obtain effective recirculation and for proper interaction between the two fluid mediums. The scrubber model was designed with three sections of baffle plates which controls and guides the flow. The mesh of scrubber model is well discretized into 1,180,000 polyhedral cells with 5,000,000 nodes.

C .Gas temperature with Injection Quantity

The water droplets are sprayed from 27 spray injection ports inside the scrubber. The boundary conditions for the water injection are prescribed in the Table II. Fig. 2 explains the reduction in temperature of the hot gas due to the injection of water droplets. The introduction of water droplets enhances the process by lowering the temperature value due to the heat exchange between the mediums. By the way, there is no much change in the temperature at the bottom section of the domain because the quantity of primary hot air is more enough in influencing the water droplets at the beginning of the process.

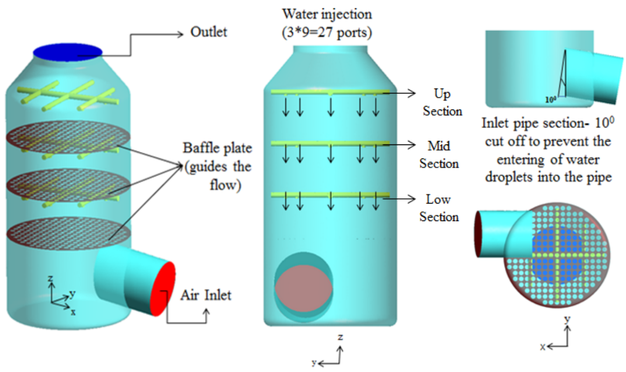


Fig. 1 Schematic representation of wet scrubber geometry

TABLE II
WATER INJECTION BOUNDARY CONDITION

Liquid gas Ratio (L/m^3)	Injection (L/min) Up	Mid	Low	Mass flow Rate (ton/hr)	Velocity (m/s)
1.5	7.8	37.5	37.5	45.61	60

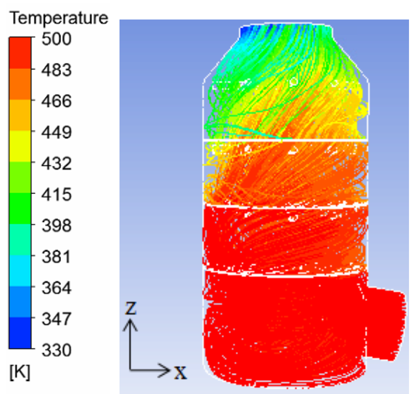
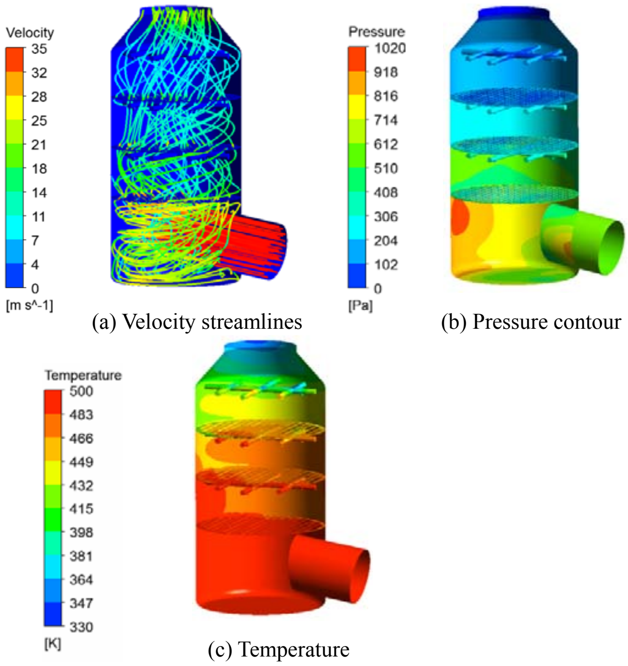


Fig. 2 Temperature contour for the hot gas temperature with injection quantity

III. RESULTS AND DISCUSSION

A. Flow Visualization

Fig. 3 represents the flow visualization indicating velocity streamlines, pressure and temperature contour of scrubber geometry. The velocity streamlines clearly predicts that the flow at the main air inlet achieves the velocity of 35m/s with the mass flow rate of 3.0556kg/s. The outlet average velocity varies at sequential time step. The pressure contour with the maximum pressure of 1020Pa is depicted on Fig. 3 (b). The pressure tends to decrease monotonically due to the cooling effect of water droplets over the hot gas. The pressure magnitude is also influenced by the impingement of water droplets. Finally, the pressure magnitude diminishes successively and equals to atmospheric pressure at the outlet.



(a) Velocity streamlines (b) Pressure contour

(c) Temperature contour

Fig. 3 Flow visualization representing (a) Velocity streamlines, (b) Pressure contour, and (c) Temperature contour

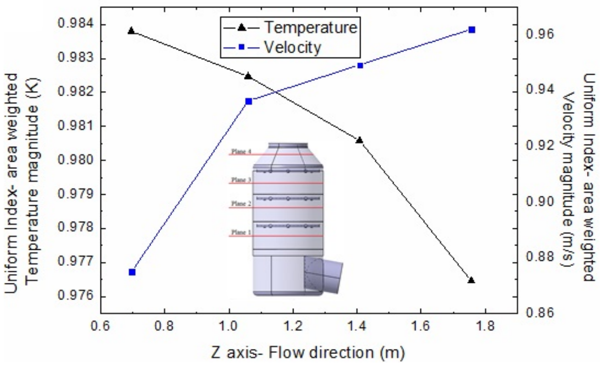


Fig. 4 Calculation of area weighted temperature and velocity magnitude along the flow direction

The temperature contour shows that the maximum temperature of 500K given as hot air inlet diminished to the temperature of 330K. The magnitude of thermodynamic parameter temperature decreases due to the temperature difference between the water droplets and the hot gas which results in heat transfer.

B. Area Weighted Uniform Index- Graphical Layout

The calculation of area weighted temperature with velocity magnitude along the flow direction was described in Fig. 4. Initially the magnitude of temperature is high because there will be less impact of water droplets over the hot gas. Eventually, the interaction between the mediums helps to drop down the temperature value indicating the successive mixing of hot gas and water droplets. The nature of the velocity flow field is adjustable with the intensive property temperature.

C. Effect of Evaporation Rate

The explanation in Fig. 5 about the DPM liquid concentration and evaporation rate plays a major role in this paper. The hot air intercepts on water droplets with the outcome of heat transfer between the two fluid mediums. Due to heat transfer, the exchange in energy enhances the rate the evaporation by the consumption of sprayed water droplets. Finally, the concentration of water droplets left in the domain will be minimizing when the evaporation rate is rich.

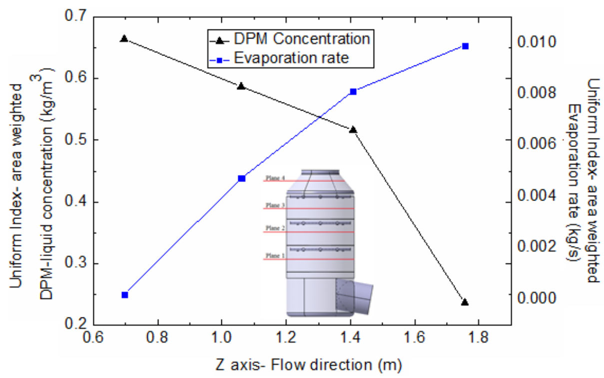


Fig. 5 Calculation of area weighted DPM concentration and evaporation rate along the flow direction

IV. Conclusion

The scrubber domain with the continuous hot gas at 500K and dispersed injection liquid at 300K are numerically simulated to analyze the flow behavior. The physical principle of the scrubber follows the reduction in domain temperature magnitude which is attained by the impingement of water droplets over the hot gas. The reduction in temperature and pressure is the evident result incurred as an outcome of cooling of hot gas by spraying water droplets. The progression in evaporation rate is by the consumption of water droplets accomplishing the conventional behavior of the scrubber system. On the other hand, the concentration of water droplets belittles due to rich in evaporation rate.

For future examination, the spray installation angle should be altered to examine the flow physics. The reason for the inclination of installation angle is for the effective mixture of hot gas and water liquid, so that the droplet distribution spreads over the entire domain and enhances the process.

From the numerical analysis conducted, it can be concluded that the simulation using ANSYS establishes the flow characteristics in relative to the domain temperature, pressure and velocity. Evaporation rate and the concentration of droplets constitute the design parameters for competent modelling.

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