

Research Article

Numerical Prediction of Water Droplet to Investigate the Evaporation Process within Venturi Tubes Under Varying Pressure Conditions

P. Charoenkitkaset*

W. Manosroi

A. Hokpunna

P. Setaphram

W. Tachajapong

Department of Mechanical
Engineering, Faculty of Engineering,
Chiang Mai University, Chiang Mai
50200, Thailand

Received 3 February 2025

Revised 25 May 2025

Accepted 16 August 2025

Abstract:

The evaporation of water droplets is influenced by various factors. Especially, pressure is a significant factor affecting the water droplets evaporation process. To study this phenomenon, the Computational Fluid Dynamics (CFD) for continuous phase flows, RANS 3D steady equations were solved in combination with the realizable k- ϵ turbulence model. Lagrangian trajectory simulations of droplets evaporation was simulated by Discrete Phase Model (DPM) and species transport model. The evaporation time of 10-micron droplets under atmospheric pressure was determined through droplets simulation. Results from comparing the droplets evaporation time, show that the evaporation times for droplets within the tube under various pressure conditions (i.e. 0.5 bar - atmospheric pressure) were 0.05002 s - 0.08235 s. This represented a decrease of 11.52% - 39.26% of the evaporation time at atmospheric pressure. Furthermore, there was observed that the droplets evaporation time is shorter under low-pressure conditions, and decreasing air pressure enhances devolatilization in water droplets. This observation led to the simulation of a venturi throat with various throat sizes and pressure conditions. This study aimed to investigate the behavior of evaporating droplets in the venturi throat. According to the results, it was observed that reducing the diameter size of the venturi throat (0.1 – 1.0 meters) led to a decrease in the droplets evaporation times by 0.41% - 26.58%. In addition, it was noted that higher speeds airflow in venturi throat result in lower air pressure and evaporation time.

Keywords: Water droplets, evaporation time, venturi throat, Computational Fluid Dynamics

1. Introduction

The saturated air is influential in the formation of aerosols and fine particles. They are essential in applications like material synthesis, pharmaceuticals, and fine powders production. In a controlled environment (such as in laboratory or industrial process), saturation facilitates particle nucleation and growth. Preliminary studies indicate that air saturation can be achieved by introducing water vapor, thereby increasing the humidity level until it reaches the saturation point. An uncomplicated approach to bring water vapor into the air involves the evaporation process achieved through the minuscule water droplets.

The evaporation processes of water droplets are subject to various factors, including pressure, temperature, velocity, droplet diameter, and the vapor diffusion coefficient. Previous studies have found that, pressure plays a pivotal role,

* Corresponding author: P. Charoenkitkaset
E-mail address: pongwrin@eng.cmu.ac.th



affecting the water droplets evaporation processes [1,2]. The evaporation time of the water droplets was shorter at low pressure conditions and reducing the air pressure results in a high level of evaporation of water droplets [3]. In addition, the evaporation rate is enhanced due to the prolonged interaction time of larger droplets with the ambient air temperature and the increased relative velocity between the air and the droplets, which consequently augments convective droplet evaporation [4].

Several studies have investigated the behavior of water droplets within Venturi tubes, emphasizing key aspects such as evaporation, dispersion, and cavitation phenomena [5,6]. These studies collectively enhance the understanding of water droplets evaporation processes in Venturi tubes and providing valuable insights for the design and optimization of such systems. However, preliminary research indicates a limited number of simulations explicitly addressing the interaction between pressure and water droplets evaporation behavior to establish optimal humidity conditions.

This research focuses on the evaporation process as part of the development and design of Evaporative condensation air purifier equipment. The equipment employing an air pressure adjustment technique using a Venturi tube to create optimal humidity conditions that enhance the condensation of water onto fine dust particles. This technique improving the efficiency of particulate removal. As pressure decreases in the Venturi throat, the saturation vapor pressure of water droplets increases relative to the ambient pressure. This phenomenon accelerates the evaporation process, as the vapor pressure gradient between the droplets surface and the surrounding air becomes more pronounced. Consequently, the mass transfer rate of water vapor from the droplets to the surrounding air is enhanced, further facilitating the evaporation process [7,8].

Accordingly, this research aims to investigate the interaction between pressure and water droplets evaporation time within the Venturi tube to identify an effective approach for generating saturated air. Additionally, the study examines the impact of air pressure variations on velocity, which directly influences the overall cost and efficiency of system implementation.

Extensive research has been studied on the evaporation processes of droplets within venturi throats, using both numerical and experimental approaches. Numerical simulation in particular has emerged as a cost-effective and reliable tool. To investigate this phenomenon, a Computational Fluid Dynamics (CFD) model was employed for simulating continuous phase flows, using 3D steady Reynolds-Averaged Navier-Stokes (RANS) equations for mass, momentum, and energy conservation, complemented by the realizable k- ϵ turbulence model [9]. In addition, Lagrangian trajectory simulations of droplets evaporation were simulated using a Discrete Phase Model (DPM) and a species transport model. The simulation results are validated by comparison with values obtained from a well-established equation for calculating water droplets evaporation as a base case. Subsequently, a computational model is developed to analyze water droplets evaporation within a Venturi tube under varying pressure conditions.

2. Methodology

In order to design a venturi tube effectively to produce large volume of saturated air, it is imperative to determine the quantity of inlet air. The inlet air conditions were specified by pressure, velocity, relative humidity, temperature, and volumetric flow rate, as illustrated in Table 1.

Table 1: Air properties at the inlet of the Venturi tube.

Dry bulb temperature	307.15	K
Wet bulb temperature	298.88	K
Relative Humidity	52.50	%
Dew point temperature	296.07	K
Density	1.1356	kg/m ³

The data presented in the table were average ambient air properties during the summer in Chiang Mai, Thailand 2020 [10].

2.1 Venturi tube design

The venturi effect occurs when fluid or air flows through the narrow section in a venturi tube, as show in Fig.1. It is a special event that occurs according to Bernoulli's principle which is a fundamental concept in fluid dynamics

involving pressure, density, velocity, and height [11]. Bernoulli's principle can be derived from the principle of conservation of energy. It states that the fluid velocity increase simultaneously with the decrease of static pressure or fluid's potential energy [12].

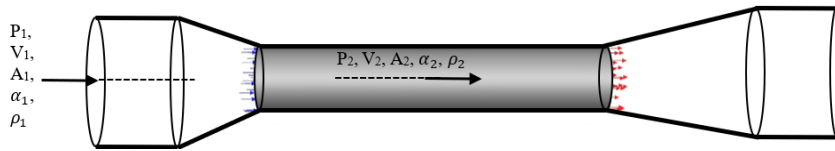


Fig. 1. Fluid flow in venturi tube.

Considering the energy equation for continuous fluid flow between two points in a viscous and incompressible fluid field, the flow characteristics of the fluid are steady state while the fluid flow velocity is unsteady. The general form of the Bernoulli's equation can be found from Eq. (1).

$$\left(\frac{P_1}{\rho_1 g} + \alpha_1 \frac{V_1^2}{2g} + Z_1\right) - \left(\frac{P_2}{\rho_2 g} + \alpha_2 \frac{V_2^2}{2g} + Z_2\right) = H_{\text{Loss}} \quad (1)$$

(with laminar flow $\alpha_1=2.0$ and turbulent flow $\alpha_1 \approx 1.05$)

Following the preliminary research, this study established specific requirement for the venturi tube components as outlined: delivery air of 2,800 m³/hr., inlet part length of 0.50 meter, inlet diameter of 1 meter. To reduce aerodynamic drag in the venturi tube, the study employs a converging section with a 30-degree angle and a diverging section with a 5-degree angle [13].

2.2 Droplets evaporation time

Since water droplets undergo rapid evaporation when injected into the venturi tube, their size must be small enough to meet the evaporation requirement. This study is thus focus on investigation 10-micron water droplets. This size was chosen because of its well-documented tendency to evaporate rapidly. It can also be easily generated using commonly available nozzles. This makes it convenient for future experiment [14].

The evaporation rate is governed by the rate at which vapor can disperse from the droplets [15]. The base case evaporation time of 10-micron water droplets was determined by the Langmuir-Maxwell method in Eq. (2) [13] and the d²-law in Eq. (3) [16,17].

$$t = \frac{R\rho_d d_d^2}{8D_v \left[\frac{P_A}{T_A} - \frac{P_d}{T_d} \right]_M} \quad (2)$$

Where droplets diffusive coefficient at 25 °C = 2.88x10⁻⁵ m²/s [18]

$$d_0^2 - d^2 = \lambda t \quad (3)$$

Where droplets evaporation constant at 25 °C = 9.37x10⁻¹⁰ s/m² [19]

From the calculation results, it was found that the variation of droplets evaporation time conforms with Eq. (2) and Eq. (3), the evaporation time of the 10-micron water droplets were around 0.1123 s and 0.1067s, respectively.

3. CFD simulation

In this research, a computational model of the 3D cylindrical venturi tube was set up for simulating the water droplets evaporation within the venturi throat at different air pressure conditions resulting from different throat sizes. Overview of the methodology is presented in Fig. 2.

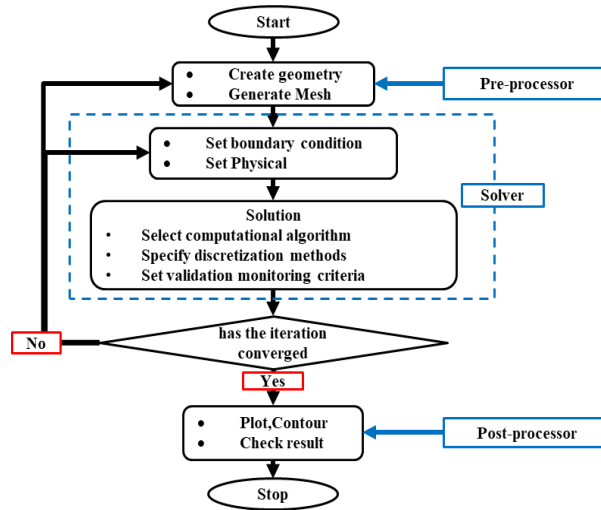


Fig. 2. Overview of the Solution Method.

3.1 Numerical modeling

3.1.1 Governing Equations

The CFD model which has been used in this study is 3D using the Lagrangian-Eulerian approach. The airflow, coupled with water droplets, was considered incompressible, steady flow in which the realizable k - ϵ turbulence model is capable to simulate. In the Lagrangian-Eulerian approach, the continuity and momentum equations were solved in the standard form, as outlined below.

- Continuity Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \quad (4)$$

The general form of the continuity equation, as presented in Equation (4), is applicable to incompressible flow conditions. The source term (S_m) accounts for the mass added to the continuous phase due to the vaporization of water droplets. In the case of an incompressible fluid, the density (ρ) remains constant.

- Momentum Equations

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \rho \vec{g} + \vec{F} \quad (5)$$

Where p denotes static pressure, $\rho \vec{g}$ represents the gravitational body force and is $\vec{F}$ external body force arising from interaction with the dispersed phase.

- Energy Equations

$$\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\vec{v} (\rho E + p)) = -\nabla \cdot \left(\sum_j h_j J_j \right) + S_h \quad (6)$$

- Species Transport Equations

$$\frac{\partial}{\partial t} (\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i \quad (7)$$

S_i , F and S_h represent the contributions from evaporating droplets, including species, forces, and evaporation energy from the water droplets. The diffusion and convection of water droplets into the surrounding air during evaporation are described by the species transport equation.

3.1.2 Discrete Phase Model (DPM)

This Model was used since the objective is to investigate particle behaviours through both Lagrangian and discrete viewpoints. DPM exchanges mass, momentum, energy, species with the continuous phase and can be solved using the Navier-Stokes equations.

Lagrangian trajectory simulations were conducted for the discrete phase, accounting for interactions between the discrete and continuous phases. The motion of the droplets was determined using a Lagrangian approach, based on Newton's Second Law, as expressed in Eq. (8).

This phenomenon occurred when the discrete phase occupies a significantly smaller volume (less than 10%) compared to the continuous phase. Following each iteration of the continuous phase calculations, the trajectories of the particles were computed and determined separately.

$$m_p \frac{dV_p}{dt} = \sum F = F_D + F_g + F_{th} + F_s \quad (8)$$

where m_p represents the mass of water droplets, while v_p denotes the velocity vector of the water droplets. As demonstrated in Eq. (9), the composite force exerted on the water droplets encompasses drag force (F_D), buoyancy and gravity force (F_g), thermophoretic force (F_{th}) and Saffman lift force (F_s). For further details, refer to [20].

The change in droplets temperature was influenced by evaporation, convection, and radiation. The energy equation for water droplets is as follows.

$$m_p c_p \frac{dT}{dt} = \pi d^2 h (T_\infty - T) + \frac{dm_p}{dt} h_{fg} + \text{Radiation} \quad (9)$$

where h_{fg} denotes the latent heat. Given the relatively low temperature range, the radiation term can be reasonably neglected. The convective heat transfer coefficient (h) can be determined through a correlation with the Nusselt number (Nu_d) or the Prandtl number (Pr) [21], as expressed in Eq. (10).

$$Nu_d = \frac{hd}{\lambda} = 2.0 + 0.6 Re_p^{0.5} Pr^{0.33} \quad (10)$$

The computation of evaporated mass involved both evaporating and boiling processes. The change of vaporization rate, was notably influenced by factors such as the relative humidity as shown in Eq. (11). This is governed by the concentration difference between the droplets surface and the air stream.

$$-\frac{dm_p}{dt} = \pi d^2 k_c (C_s - C_\infty) \quad (11)$$

where C_s represents the vapor concentration and k_c denotes the mass transfer coefficient at the droplets surface. The evaluation of the droplets surface was conducted under the assumption that the flow over the surface remains in a saturated state. C_∞ denotes the vapor concentration in the bulk flow, which is obtained by solving the transport equation within the computational cell. The coefficient k_c can be determined using Eq. (12), as shown below:

$$Sh_d = \frac{k_c d}{D} = 2.0 + 0.6 Re_p^{0.5} Sc^{0.33} \quad (12)$$

where Sh_d denotes the Sherwood number, Sc denotes Schmidt number. The evaporation rate can be estimated using the following equation when the droplets temperature reaches the boiling point.

$$-\frac{dm_p}{dt} = \pi d^2 \left(\frac{\lambda}{d} \right) (2.0 + 0.46 Re_d^{0.5}) + \ln(1 + C_p(T_\infty - T)/h_{fg})/C_p \quad (13)$$

Where λ represents the thermal conductivity of the gas or air, and c_p denotes the specific heat capacity of the bulk flow.

The evaporation of water droplets occurs in two stages. In Stage 1, when the temperature exceeds the saturation temperature, evaporation is driven by vapor partial pressure (Eq. 11) until the air reaches 100% relative humidity. In Stage 2, once the temperature reaches the boiling point, evaporation follows Eq. 13. After evaporation, whether due to low moisture partial pressure (Stage 1) or high temperature (Stage 2), the resulting water vapor is transported away by convection and diffusion, as described in the water vapor transport equation (Eq. 7).

3.1.3 Turbulence model

In this study, the simulation of Particle-Laden Flows using the realizable k- ϵ model was employed. Preliminary studies have examined the impact of various turbulence models, including the standard k- ϵ model, RNG k- ϵ model, realizable k- ϵ model, standard k- ω models, and Reynolds stress model, on the results of evaporative cooling in water spraying simulations. The findings indicated that no turbulence model was considered superior to other models [22]. However, realizable k- ϵ model was selected as the primary model for analysing the results because the realizable k- ϵ model effectively captures turbulence characteristics in various complex flow scenarios, including swirling flows commonly observed in venturi tubes and curved streamline flows influencing water droplets trajectories [23,24,25,26]. Additionally, this model allows precise tracking of individual droplets, their motion, and evaporation rates, making it highly compatible with the Discrete Phase Model (DPM) used in CFD [27,28].

The realizable k- ϵ model is a two-equation turbulence model that relies on the Boussinesq assumption. It includes transport equations for turbulent kinetic energy (k) and the dissipation rate (ϵ), allowing for a more accurate representation of turbulent flow characteristics. This model enhances the prediction of turbulence by improving the formulation of the dissipation rate equation, making it particularly effective for complex flow scenarios. [15][29]. The formulated transport equations for k and ϵ in this model are provided in Eq. (14) and Eq. (15).

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\mu_t}{\sigma_k} \frac{\partial^2 k}{\partial x_j \partial x_j} + G_k + G_b - \epsilon - Y_M + S_k \quad (14)$$

$$\frac{\partial \epsilon}{\partial t} + U_j \frac{\partial \epsilon}{\partial x_j} = \frac{\mu_t}{\sigma_\epsilon} \frac{\partial^2 \epsilon}{\partial x_j \partial x_j} + C_1 S_\epsilon - C_2 \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} + C_3 \frac{\epsilon}{k} G_b + S_\epsilon \quad (15)$$

The eddy viscosity is presented in Eq. (16)

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \quad (16)$$

C_μ is presented in Eq. (17)

$$C_\mu = \frac{1}{A_0 + A_s \frac{k U^*}{\epsilon}} \quad (17)$$

The constants for this model in this study are as follows:

$$C_1 = 1.44, C_2 = 1.9, \sigma_k = 1.0, \sigma_\epsilon = 1.2 \quad (18)$$

3.1.4 Near-wall Turbulence

To evaluate the effect of viscosity within the viscous sublayer, the computational grid in this region must be sufficiently fine to allow accurate calculations. The Y^+ values for each layer are categorized as follows: $Y^+ < 5$ for the viscous sublayer, $5 < Y^+ < 30$ for the buffer layer or blending region, and $Y^+ > 30$ to 60 for the fully turbulent or log-law layer.

For detailed calculations within the viscous sublayer and buffer layer, the centroid of the first grid cell should be positioned at approximately $Y^+ \approx 1$ [30]. Prior to generating the computational grid, the Y^+ value can be estimated using the following equation:

$$Y^+ = \frac{yu_\tau}{\nu} \quad (18)$$

3.2 Geometry and Grid

A 3D computational domain of cylindrical tube with a diameter of 0.1-1.0 meters and a length of 1.5 meters was established to study water droplets evaporation processes to create saturated air in venturi tube, and simulating the variation in water droplets evaporation due to a decrease in air pressure resulting from the reduction in venturi throat size. The Ansys Fluent Design Modeler was used to create geometry and generate a mesh, resulting in the formation of polyhedral mesh elements as outlined in Fig. 3.

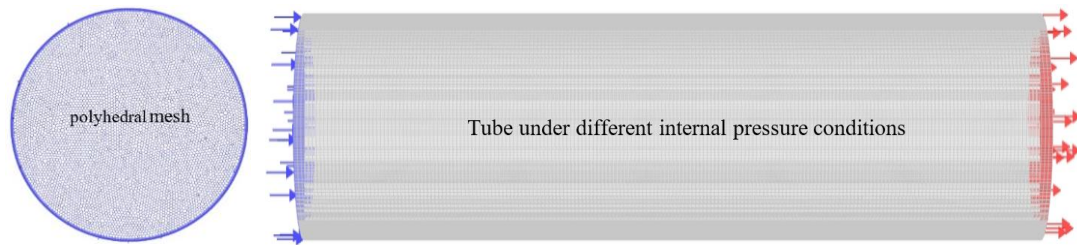


Fig. 3. Geometry and polyhedral mesh generation.

3.2.1 Mesh Independence Study

A mesh independence study was performed to provide a solution that is independence of mesh accurately capturing the pressure inside the tube [31]. Changes in the average pressure caused by different mesh resolution were observed at the midpoint of the tube. The minimum number of mesh elements suitable for this computational model, is listed in Table 2.

Table 2: Mesh independence study.

Venturi throat diameter (meter) mesh elements	Minimum
1.00	20,711,747
0.90	16,776,515
0.80	13,255,518
0.70	10,148,756
0.60	7,456,229
0.50	5,177,937
0.40	3,313,880
0.30	1,864,058
0.20	828,470

3.2.2 Boundary conditions

The inlet boundary condition of the domain was specified by temperature, relative humidity, velocity and pressure. They were 1.00 m/s, with a relative humidity of 52.50 % and 307.15K while the pressure depends on the reduction in the size of the venturi throat.

3.2.3 Characteristics of the spray nozzle

The cone spray model from Ansys Fluent was used. Water droplets of 10-micrometers size were injected into the computational domain through a nozzle with a cone angle of 90-degree and a diameter of 1 mm. This nozzle was located horizontally downstream at the center of the inlet plane within the computational domain as shown in Fig.4

3.2.3 Solver settings

The PISO algorithm by Issa (1986) was used for pressure-velocity coupling in solving the governing equations [24]. Second-order discretization scheme was used for both convection and viscous terms in the equations for solving the

pressure interpolation. Solution convergence was considered when the normalized residual for each conservation equations equals or less than 10^{-6}

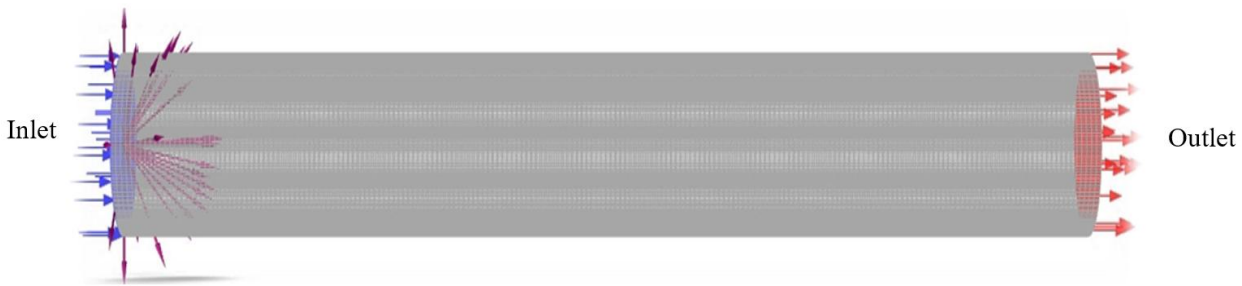


Fig. 4. Position and direction of Cone Spray.

4. Results and discussions

Evaporation occurs on the surface area of droplets when the droplets molecules impact and transfer energy to each other. When the molecules near the surface absorbs enough energy to overcome the vapor pressure, it transitions into a gas in the surrounding air. In this study, the evaporation processes of 10-micron water droplets within a tube were simulated by CFD model. The simulation incorporated both the Discrete Phase Model (DPM) and species transport model, allowing for predictions under varying pressures. The influence of internal pressures in tube on the evaporation process was investigated.

4.1 Evaporation of 10-micron water droplets

The base case evaporation time of 10-micron water droplets at atmospheric pressure were determined using Eq. (2) and Eq. (3). This was then compared with the evaporation time obtained from the water droplets simulation. This study simulates the evaporation process of water into the air with a volume of 70.56 m³/hr. The air temperature was 307.15 K with a relative humidity of 52.50% as shown in the Table 2.1. A mono-disperse spray with a 10-micron water droplets volume of 1.88x10⁻¹⁰ ml/hr. at 298.15 K was injected at the center of the venturi throat. The 3D cylindrical tube computational domain was created with a diameter of 0.5 meters and a length of 1.5 meters. The geometry and mesh generation were performed with the Ansys fluent design modeler. The optimal mesh was found to consist of 5,177,937 polyhedral elements. as shown in Fig. 5.

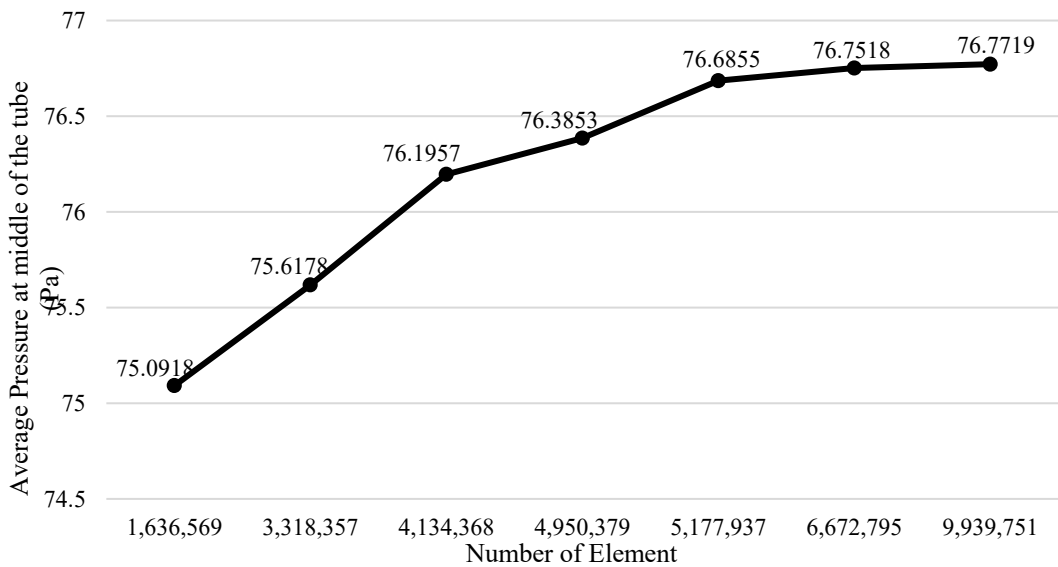


Fig. 5. Mesh independence study.

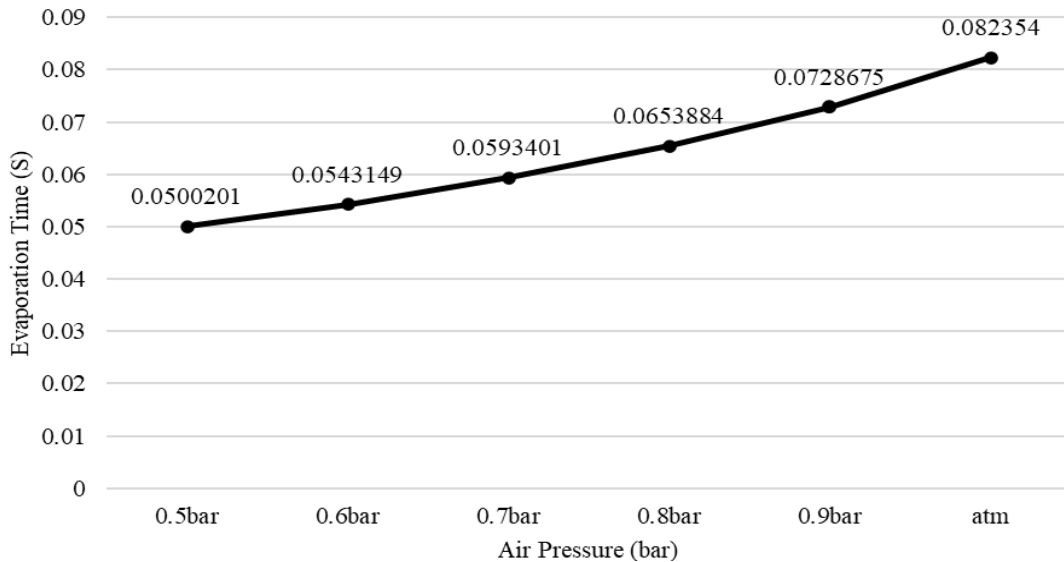
Table 3: comparing the water droplets evaporation time at atmospheric pressure.

Droplet size	Evaporation time by Eq. (2)	Evaporation time by Eq. (3)	Evaporation time by simulation
10 microns	0.1123 s	0.1067 s	0.0824 s

By comparing the droplets evaporation time that shows in Table 3, it is found that the simulated evaporation time was similar to the base case value at atmosphere pressure. Moreover, The variation in water droplets diameter aligns with the evaporation time observed in multiple studies on droplets evaporation in air. Previous studies have shown that 10-micron water droplets typically evaporates within approximately 0.1 s, depending on ambient humidity and temperature conditions [32,33,34]. Additionally, pressure is a key factor influencing the evaporation of water droplets. Investigating the effects of pressure variations on droplet evaporation enhances the understanding of evaporation dynamics, facilitating its efficient application in various devices. The simulation results are presented as follows.

4.1.1 Residence time of water droplets at different air pressure

The simulation results reveal a clear correlation between pressure and the evaporation time. The evaporation times in the tube under 0.5 bar, 0.6 bar, 0.7 bar, 0.8 bar, 0.9 bar, and atmospheric pressure were 0.05002 s, 0.05431 s, 0.05934 s, 0.06539 s, 0.07286 s, and 0.08235 s, respectively, as shown in Figure 6. They decreased by 39.26%, 34.05%, 27.94%, 20.60% and 11.52%, respectively, when compared with the evaporation time at atmospheric pressure.

**Fig. 6.** Relationship between droplets evaporation time and air pressure.

From the Fig. 6, it can be seen that the evaporation time increases with the pressure conditions. A longer evaporation time of water droplets are observed with higher air pressure values.

4.1.2 Devolatilization of water droplets at different pressure

The devolatilization process of water droplets was taken into account to analyze the evaporation time across different pressure ranges. Simulation results indicate that pressure influences the devolatilization of water droplets. Based on simulation results, the devolatilization of water droplets at 0.9 bar, 0.8 bar, 0.7 bar, 0.6 bar, and 0.5 bar were increased respectively. The average devolatilization rates increased by 16.85%, 36.15%, 54.48%, 71.95%, and 90.36%, respectively. Similarly, the maximum devolatilization rates increased by 13.49%, 26.56%, 39.40%, 52.09%, and 64.96%, respectively, when compared with the devolatilization of water droplets at atmospheric pressure, as illustrated in Fig. 7.

From Fig. 7, it is evident that the maximum and average values of water droplets devolatilization increase as air pressure decreases. However, the difference between the maximum and average values increases when the air

pressure decreases. This implies that the lower air pressure, the faster evaporation process will occur. This is followed by a subsequent decrease until the evaporation process is complete, as shown in Fig. 8.

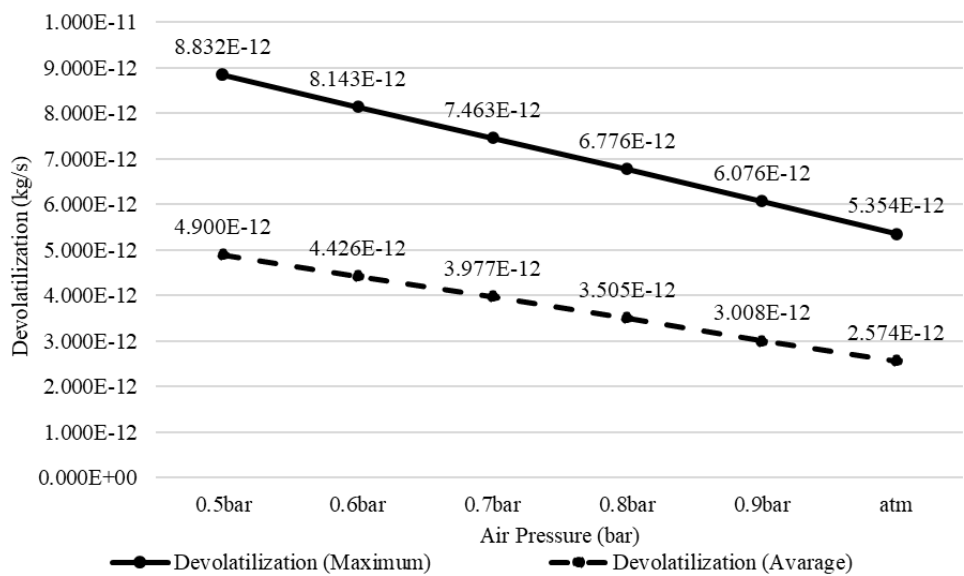


Fig. 7. Relationship between devolatilization of water droplets and air pressure.

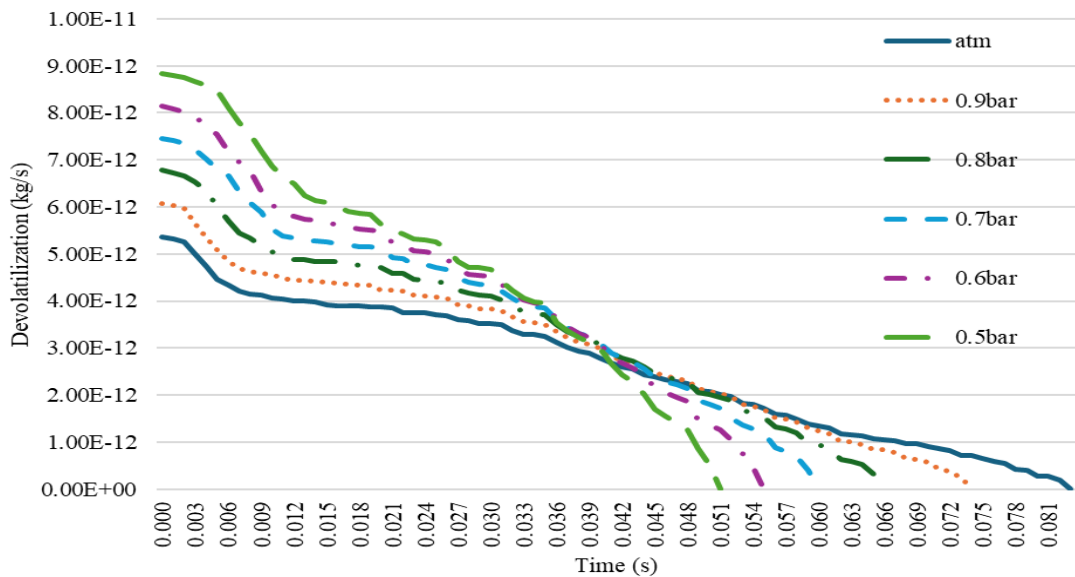


Fig. 8. Relationship between water droplets devolatilization and evaporation time.

4.1.3 Droplets mass and evaporation time at different pressure

According to Fig. 9, evaporation of water droplets occurs rapidly, especially under condition of reduced air pressure. The devolatilization was higher at the beginning of the evaporation process than at the end. The initial mass of a 10-micron droplets was 5.226563×10^{-13} kg. The droplets mass decreases rapidly during the initial stage because the larger surface area facilitates evaporation. In additional, the reducing the air pressure also accelerates the reduction of droplet mass.

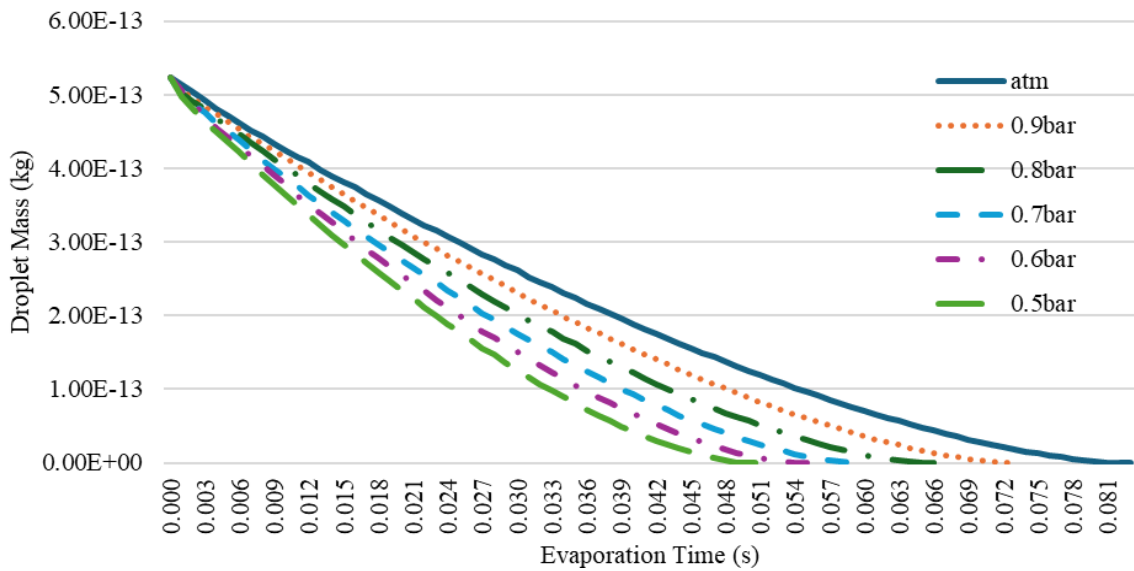


Fig. 9. Relationship between droplets mass and evaporation time.

4.1.4 Droplets diameter and evaporation time at different pressure

In contrast to the mass of water droplets, the diameter decreases slowly during the initial stage of evaporation process, This is because of the surface area is larger. However, the decrease in air pressure has a significant impact on reducing the diameter of water droplets, as shown in Fig. 10.

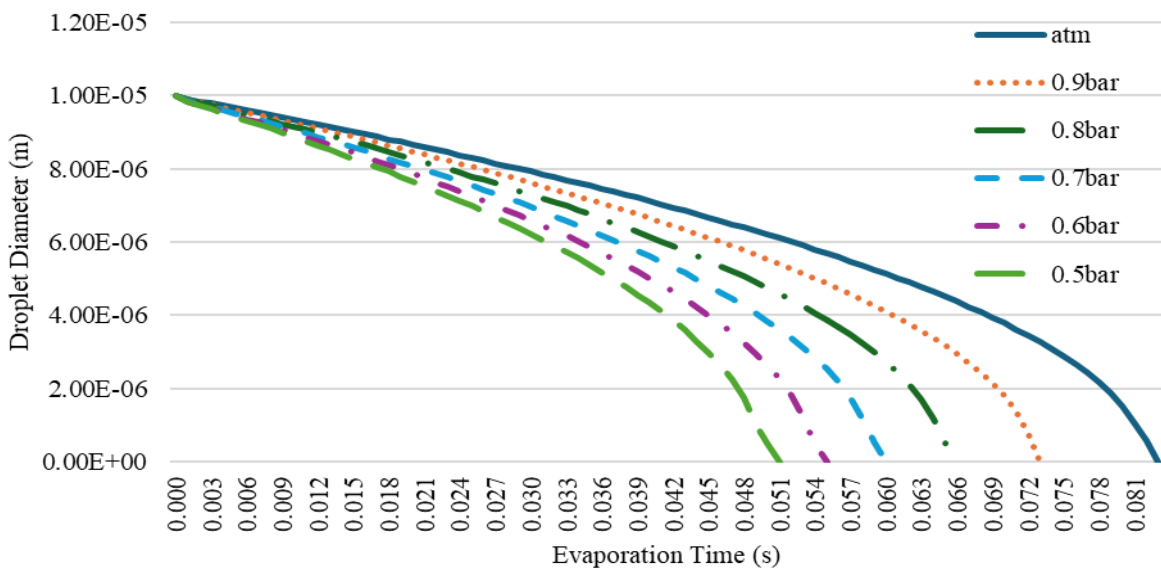


Fig. 10. Relationship between water droplets diameter and evaporation time.

4.2 Evaporation of 10-micron water droplets in different Throat diameter and length

Simulations reveal that the evaporation process is responsive to changes in pressure, as shown in Fig. 6. It is clear that under lower pressure conditions, the evaporation time of water droplets is reduced. This is because reducing the air pressure causes water droplets to evaporate at a higher level. Therefore, different throat size will affect the pressure inside the throat and affect the evaporation behavior in venturi tube consequently.

This study simulates the evaporation process of water into the air with a volume of 2,800 m³/hr. The air temperature was 307.15 K with a relative humidity of 52.50% as shown in the Table 1 From the psychrometric chart, it was found that approximately 20.77 ml of water per cubic meter of dry air needed to be evaporated to achieve a relative humidity level of 100%.

A mono-disperse spray consisting of 1,000 streams with a 10-micron water droplets volume of 20.77 ml/m³dryair at 298.15 K was injected at the center of the venturi throat. Airflow is considered incompressible. The air velocity in the venturi throat remained lower than 105.372 m/s (i.e.a Mach number below 0.3 [35]) as shown in Table 4.

Table 4: Simulation data of Droplets evaporation time in different Throat diameter.

Venturi throat diameter (meters)	Venturi throat air velocity (m/s)	Venturi throat air pressure (pascal)	Venturi throat Cross-sectional area (m ²)	Venturi throat minimum length (m)
1.0	1.00	Atm	0.785	1.033
0.9	1.23	101324.70	0.636	1.265
0.8	1.56	101324.20	0.503	1.598
0.7	2.04	101323.20	0.385	2.087
0.6	2.78	101321.20	0.283	2.534
0.5	4.00	101316.50	0.196	3.614
0.4	6.25	101303.40	0.126	5.429
0.3	11.11	101255.50	0.071	9.519
0.2	25.00	100970.70	0.031	20.889
0.1	100.00	95647.57	0.008	75.818

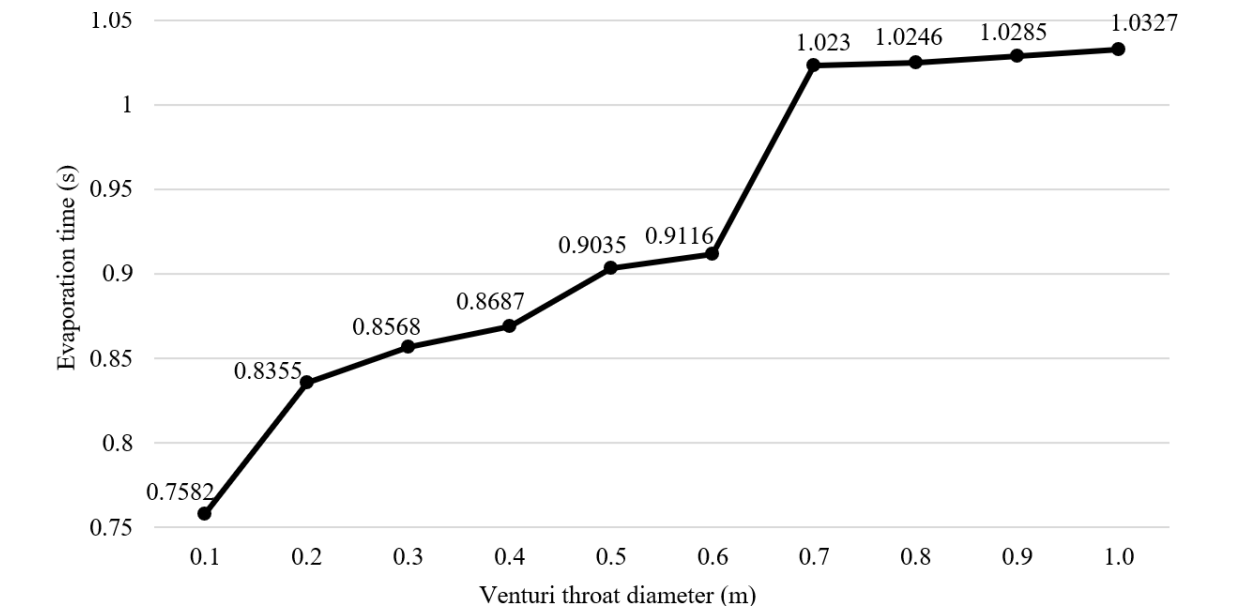


Fig. 11. Relationship between venturi throat diameter and evaporation time.

According to Table 4 and Fig. 11, reducing the diameter of the venturi throat (from 1.0 to 0.1 m) result in a decrease in the air pressure within the throat. Hence, the evaporation time of water droplets is reduced. The change in evaporation time when the diameter size of the venturi throat was 1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2 and 0.1 meter decreased by 0.41 %, 0.78 %, 0.94 %, 11.73 %, 12.51 %, 15.88 %, 17.03 %, 19.09 % and 26.58 %, respectively. When assessing the venturi throat length used for evaporation of water droplets, it was observed that a smaller cross-sectional area in the venturi throat result in faster airflow (maintained the same volume). While reducing the air pressure decreases the evaporation time of droplets. The increase in air velocity corresponds to an increase in the calculated length of the venturi throat as shown in Table 4.

5. Conclusions

- A clear inverse relationship was observed between varying air pressure and the evaporation time of 10-micron water droplets within the Venturi tube. Specifically, a lower pressure condition (0.5 bar) resulted in a 39.26% reduction in evaporation time compared to atmospheric pressure. This reduction is attributed to enhanced devolatilization under reduced pressure, which accelerates mass loss from the droplets. These findings are consistent the Clausius–Clapeyron relation, which describes how reduced pressure lowers equilibrium vapor pressure and promotes faster evaporation [36].

- Reducing the diameter of the Venturi throat leads to a significant decrease in internal pressure, an increase in airflow velocity, and a corresponding reduction in water droplet evaporation time. Although a smaller throat diameter enhances the evaporation rate due to reduced pressure and increased flow velocity, it may also necessitate longer pipe lengths to ensure sufficient vapor residence time for complete evaporation. Therefore, practical design considerations must balance performance efficiency with cost-effectiveness and spatial constraints.

- Although theoretical models describe the relationship between air pressure and droplet evaporation, empirical studies focusing on pressure variation in Venturi throats are still limited. This highlights a need for further experimental studies to bridge the gap between theoretical predictions and practical applications.

Nomenclature

P_1	Pressure of air at position 1 (kPa)
ρ_1	Density of air at position 1 (kg/m^3)
α_1	Coefficient of kinetic energy at position 1 (with laminar flow $\alpha_1=2.0$ and turbulent flow $\alpha_1\approx 1.05$)
V_1	Velocity of air at position 1 (m/s)
Z_1	Height from reference at position 1 (m)
P_2	Pressure of air at position 2 (kPa)
ρ_2	Density of air at position 2 (kg/m^3)
α_2	Coefficient of kinetic energy at point 2
V_2	Velocity of air at position 2 (m/s)
Z_2	Height from reference at position 2 (m)
g	Acceleration of Earth's gravity (m/s^2)
H_{Loss}	Losses in the venturi tube (m)
R	Ideal gas constant ($\text{J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$)
D_v	Droplet diffusive coefficient (m^2/s)
ρ_d	Droplet density (kg/m^3)
d_d	Droplet diameter (m)
P_d	Pressure on the surface of droplet (kPa)
T_d	Temperature on the surface of droplet (K)
P_A	Air pressure (kPa)
T_A	Air temperature (K)
d_0^2	Initial diameter of droplet (m)
d^2	Final diameter of droplet (m)
λ	Droplet evaporation constant (s/m^2)
u_τ	Friction velocity (m/s)
y	Absolute distance from the wall (m)
ν	Kinematic viscosity (m^2/s)

References

- [1] Kumar J, Singh J, Kansal H, Narula GS, Singh P. CFD Analysis of Flow Through Venturi. International Journal of Research in Mechanical Engineering and Technology. 2014;4(2):214–217.
- [2] Özgür E, Koçak K. The Effects of the Atmospheric Pressure on Evaporation. Acta Geobalkanica. 2015;(1):17–24.

- [3] Charoenkitkaset P, Setaphram P, Saedan M, Hokpunna A, Manosroi W, Tachajapong W. Numerical Prediction of Evaporation Time Under Different Air Pressure Conditions by Discrete Phase Model. In: Proceedings of the 13th TSME International Conference on Mechanical Engineering, Thailand. 2023;421–433.
- [4] Sommerfeld M, Qiu HH. Experimental Studies of Spray Evaporation in Turbulent Flow. *International Journal of Heat and Fluid Flow*. 1998;10–22.
- [5] Setaphram P, Charoenkitkaset P, Saedan M, Hokpunna A, Manosroi W, Tachajapong W. Experimental Evaluation of a Spray Humidifier as an Evaporative Process. In: Proceedings of the 13th TSME International Conference on Mechanical Engineering, Thailand. 2024;3236(1).
- [6] De la Cruz-Ávila M, De León-Ruiz JE, Carvajal-Mariscal I, Klapp J. CFD Turbulence Models Assessment for the Cavitation Phenomenon in a Rectangular Profile Venturi Tube. *Fluids*. 2024;9(3):71.
- [7] White FM. *Fluid Mechanics*. 8th ed. New York: McGraw-Hill Education; 2016.
- [8] Fox RW, Pritchard PJ, McDonald AT. *Introduction to Fluid Mechanics*. 9th ed. Hoboken: Wiley; 2019.
- [9] Lorenzini G, Conti A, De Wrachien D. Computational Fluid Dynamics (CFD) Picture of Water Droplet Evaporation in Air. *Irrigation and Drainage Systems Engineering*. 2012;1(1).
- [10] Climatological Center, Meteorological Department Thailand. Monthly and Annual Mean Temperature of Thailand. 2020.
- [11] Clancy LJ. *Aerodynamics*. New York: Wiley; 1975.
- [12] Batchelor GK. *An Introduction to Fluid Dynamics*. Cambridge: Cambridge University Press; 2000.
- [13] Nasr GG, Connor N. Gas Flow Measurement. In: *Natural Gas Engineering and Safety Challenges*. Springer; 2014:183.
- [14] Zheng Q, Sun Y, Li S, Wang Y. Thermodynamic Analysis of Wet Compression Process in the Compressor of Gas Turbine. In: Proceedings of ASME Turbo Expo; 2002 Jun 3–6; Amsterdam, Netherlands. 2002.
- [15] Hinds WC. *Aerosol Technology: Properties, Behavior and Measurement of Airborne Particles*. New York: Wiley; 1999.
- [16] Ochowiak M., Bielecki Z., Bielecki M., Włodarczak S., Krupińska A., Matuszak M., Choiński D., Lewtak R., Pavlenko I. The D2-Law of Droplet Evaporation When Calculating the Droplet Evaporation Process of Liquid Containing Solid State Catalyst Particles. *Energies*; 2022.
- [17] Wei Y. Effect of Particles on Evaporation of Droplet Containing Particles. Orlando: University of Central Florida; 2015.
- [18] Cussler EL. *Diffusion: Mass Transfer in Fluid Systems*. New York: Cambridge University Press; 1997.
- [19] Ragab R, Wang T. An Investigation of Liquid Droplet Evaporation Model Used in Multiphase Flow Simulation. American Society of Mechanical Engineers International Mechanical Engineering Congress and Exposition. 2012;7:485–497.
- [20] ANSYS Incorporated. ANSYS Fluent Tutorial Guide. Release 18.0. 2017.
- [21] Ranz WE, Marshall WR Junior. Evaporation of Water from Drops. *Chemical Engineering Progress*. 1952;48(3):141–180.
- [22] Montazeri H, Blocken B, Hensen JLM. Evaporative Cooling by Water Spray Systems: CFD Simulation, Experimental Validation and Sensitivity Analysis. *Building and Environment*. 2015;83:129–141.
- [23] Siriboonluckul N, Juntasaro E, Juntasaro V. Application of Omega–K Turbulence Model for Particle-Laden Flows. In: Proceedings of the Conference on Mechanical Engineering Network of Thailand; 2004 Oct 18–20; Khon Kaen, Thailand. 2004
- [24] Marzouk OA, Huckaby ED. Simulation of a Swirling Gas-Particle Flow Using Different K-Epsilon Models and Particle-Parcel Relationships. *Engineering Letters*. 2010;18(1).
- [25] ANSYS. *Fluent Theory Guide: Discrete Phase Modeling for Evaporation and Condensation*. Canonsburg: ANSYS Incorporated; 2023.
- [26] ANSYS. *Fluent User Guide: Turbulence Models for Multiphase Flow*. Canonsburg: ANSYS Incorporated; 2023.
- [27] Wilcox DC. *Turbulence Modeling for CFD*. DCW Industries; 2006.
- [28] Pope SB. *Turbulent Flows*. Cambridge: Cambridge University Press; 2000.
- [29] Persson T. Eulerian-Lagrangian Modeling of Multicomponent Spray for Aseptic Treatment of Carton Bottles in the Food Process and Packaging Industry. Gothenburg: Chalmers University of Technology; 2013.
- [30] ANSYS. *Fluent 6.2 User's Guide*. Canonsburg: ANSYS Incorporated; 2013.
- [31] Abd Halim MAA, Nik Mohd NAR, Mohd Nasir MN, Dahalan MN. The Evaluation of k-epsilon and k-omega Turbulence Models in Modelling Flows and Performance of S-shaped Diffuser. *International Journal of Automotive and Mechanical Engineering*. 2018;15(2):5161–5177.

- [32] Ji Y, Qian H, Ye J, Zheng X. The impact of ambient humidity on the evaporation and dispersion of exhaled breathing droplets: A numerical investigation. *Journal of Aerosol Science*. 2018;115:164–172.
- [33] Kurai K, Miyamoto H, Takegawa N. Evaporation of Water from Airborne Droplets Containing Sodium Chloride, Mucin, and Surfactant. *Aerosol Air Quality Research*. 2024;24(7):240025.
- [34] Li X, Shang Y, Yan Y, Yang L, Tu J. Modelling of evaporation of cough droplets in inhomogeneous humidity fields using the multi-component Eulerian-Lagrangian approach. *Building and Environment*. 2017;128:68–76.
- [35] Anderson JD. *Fundamentals of Aerodynamics*. 4th ed. McGraw-Hill; 2007.
- [36] Glasser MB. The Clausius–Clapeyron Equation Revisited. *European Journal of Physics*. 2003.