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Enhancement of Methane-Air Combustion with Increasing Oxygen Ratio

Hussein M. Salih*, Adel H. Ayaal

Electromechanical Engineering Department, University of Technology, Baghdad 19006, Iraq

Corresponding Author Email: 50004@uotechnology.edu.iq

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ABSTRACT

Increasing combustion efficiency and minimal emissions of pollutants are among the fundamental issues in combustion research. In this regard, the phenomenon of combustion and its influencing factors, such as the fuel / air ratio as one of the most important factors in flame formation, have attracted the attention of many researchers. In this study, the effect of increasing the oxygen ratio over its proportion in the stoichiometric reaction for methane – air combustion was studied. The equations for the conservation of mass, momentum, and energy for a methane-air mixture have been solved by using CFD. A FORTRAN-90 program based on GENMIX will be developed. In order to verify the validity of the present program, the present numerical results were compared with the previous experimental results, and the comparison showed a good agreement. From the results, it was found that increasing the proportion of oxygen leads to an improvement in the temperature distribution inside the combustion cylinder, and there is no effect was observed on the nature of the velocity profiles inside the combustion space. As for the combustion of fuel, there was an improvement in the fuel combustion rate with the increasing in oxygen ratio.

1. INTRODUCTION

Combustion is the burning of biofuels with air, which is usually carried out in the atmosphere, where atmospheric air consists of 21% oxygen and nitrogen, which makes up about 79%. Oxygen is the oxidizing agent in the fuel combustion process, so in order to obtain a complete combustion of the fuel and the highest possible value of thermal efficiency, the combustion is enriched with an additional amount of oxygen. As a result, many theoretical and experimental studies have emerged that deal with this topic with study and analysis, and one of these studies, the current study.

In general, combustion enters into many applications in our daily lives, including heating water in domestic heaters to reactors of aircraft and marine ships. Given the importance of this phenomenon which is the main source of heat used in industry, it leads to a very popular field of study for many reasons [1, 2]. The following paragraphs can explain some of these reasons.

First, combustion is a major source of energy, as researchers seek to maximize the efficiency of combustion systems and obtain maximum resource profit. Second, the concern is not only to increase efficiency but also to make these processes environmentally friendly, and one of the most limiting aspects of improving combustion systems is the pollution generated by it.

On the other hand, computational resources are developing at an astonishing speed, allowing simulations of such applications with an accuracy and speed that was not available in previous years. On the other hand, the use of simulation allows reducing the time spent in the investigation because the use of the computation can save time and money spent on expensive experiments [3]. In the following paragraphs, some of these numerical and experimental studies will be reviewed.

Xu et al. [4] studied combustion with verity of oxygen concentrations and velocities of (19.5−36%) and (47.16−261.18 m/s) respectively numerically. The results showed that enrichment of oxygen yields an increasing in temperature and NOx emissions. Effect of gas injection on efficiency for the burning of gaseous fuels was studied by Kiverin et al. [5]. A coaxial burner is offered with an inner wall perforated in it. The acceleration of methane-air was observed. It was numerically verified that the acceleration of the flame is related to the separation of the flow from the inner wall, which is a key factor in Reduce wall heat loss as well as vortex formation and reduce momentum loss. The effects of hydrogen mixture on pressurized oxygen fuel combustion had been studied by Park et al. [6] to improve hydrogen infrastructure and decreasing greenhouse gas emissions. A counter flow propagation flame model was employed. A counter flow propagation flame model was employed to describe the properties of POFC. Refined and unpurified natural gas was used as fuel. Yue et al. [7] Presented an experimental and numerical study on the combustion of light-air methane pre-mixed in an industrial porous medium burner consisting of intertwined alumina cylinders. Numerical simulations were performed with gas mixture velocities from 0.43 to 866 m/s and equivalence ratio of 0.162 and 0.243 respectively. Gao et al. [8] Presentation of a numerical study of a two-dimensional methane/air mixture combustion model in a catalytic and non-catalytic porous medium. By changing operating parameters, burner structure, and physical properties of alumina pellets, the distribution of temperature and stability of combustion flame in inert alumina (Al_2O_3) pellets and platinum (Pt) catalyst-supported alumina (Al_2O_3) pellets, were studied. From this study, the authors conclude that the difference in the location of the flame between the catalytic burner and the inert pore becomes smaller as the inlet velocity increases, while the distance of the flame site to the burner inlet is approximately constant as the length of the porous media of both the catalytic and inert porous burner increases, while the relative position of the flame site moves upstream. By using the ANSYS-Fluent CFD code, Hosseini et al. [9] presented a study of the effect of swirl number of entering air for methane- air diffusion flame on the nature of the dynamic flux and the distribution of radiant heat flux. A particular equation in terms of tangential and axial velocity components was proposed to achieve the swirl number depending on the effect of swirling on the dynamic flow behavior. Eddy Dissipation Model (EDM) was utilized to perform chemical reaction modeling. In addition, P-1 and k-ε standard models were used to study the characteristics of radiative heat flow and turbulent flow. From results, there was an increase in the number of incoming air vortices within a range of 0.0 to 0.6 develops the inner recycling section of the furnace, which produces the products of combustion in the inner recycling section. Thus, the fuel and air are mixed well to obtain high combustion efficiency by removing high temperature zones as they are the main cause of nitrogen oxides (NOx) production. Fomenko et al. [10] presented a numerical study of methane-air combustion in a direct flow burner. Five burner operating modes were simulated depending on the boiler load by utilizing ANSYS. The aim of this study was to examine the effects of replacing existing vortex stoves in facilities which described previously with direct flow stoves while regulating the new combustion process. A partial reaction was observed as a result of pre-mixing natural gas with air, which results in an increase in the temperature of the fuel-air mixture and the formation of combustion products in the flow. Shu et al. [11] presented a study of the effect of lean combustion on the nature of combustion and emissions for a diesel natural gas engine by using the CFD with conjugate with the reduced kinetic chemical model. The simulated results showed that, less than 50% of the load, the cylinder pressure increases and the combustion onset is advanced when the excess air coefficient increases from 1.0 to 1.5, and the maximum combustion initiation progression is up to 9.5°C. Yan et al. [12] mainly studied the influence of controllable slot width in a micro-combustion device with a two-sided slot illusion body. They concluded that a controllable narrow slot width can greatly improve combustion efficiency.

The combustion properties of methane/air in a micro-combustion apparatus were investigated by Yan et al. [13] with a regular triangular pyramidal trick body. The results showed that the blowing limit in the micro combustion apparatus with a regular triangular pyramid bluff body is 2.4 times that in the micro combustion apparatus without the bluff body. Furthermore it, as the entrance speed increases, the recirculation area expands and the effect of the preferential transfer increases behind the bluff-body. Reyes et al. [14] presented a study to determine the velocities of combustion depending on the use of combustion bomb. Where the evolution of tentative pressure is recorded. The experimental pressure trace was analyzed using a two-zone combustion model, where thermodynamic variables that cannot be measured directly were found. For stoichiometric conditions, results were correlated for the burning velocity of hydrogen/air mixtures, up to 1.6 Mpa and 650 K. The proposed correlation had been verified by comparing results with other published correlations. Li et al. [15] presented a numerical study to simulate the combustion process of an NG-diesel dual-fuel engine using CFD CONVERGE model associated with a reduced primary reference fuel (PRF). Through the results, it was found that the momentum generated by the injection of the pilot fuel and the combustion led to the transfer of the combustion products to the pilot fuel and methane Inside the pilot spray column towards the mixture of methane and unburned air. Pashchenko [16] proposed a numerical study of a micro-cylindrical premixed hydrogen-air combustor utilizing RANS. The effect of the geometrical dimensions of the computation field was studied by performing numerical simulations using two-dimensional planar, two-dimensional axisymmetric and three-dimensional. From results, it is noted that the difference between the temperature of combustion products at the outlet section of the combustor for the three- and two-dimensional geometries is more than 25%, and for the range of the flame formation the temperatures vary by several times. Yilmaz et al. [17] studied micro-combustion by adding a backward-facing step, a cavity, and multiple channels. The results demonstrated a more significant effect of narrow channel height on the temperature distribution and emitted NOx ratios than the backward-facing gradient arrangement in the hydrogen/air pre-mixed micro-shells. Whereas Zuo et al. [18] used a micro-elliptical tube combustion apparatus to study the combustion performance of the pre-mixed H_2/air numerically. From the study it was found that the emission and combustion efficiency was higher using the small oval tube compared to the small round tube. Besides, Yan et al. [19] presented a numerical study of the catalytic combustion of a combustion device with/without preheating channels. In their study, preheating channels facilitated the effect of heat recycling, and the heat recycling rate exceeded 10% for all cases. Zhang et al. [20] presented a numerical study to simulate the combustion of pre-mixed methane/lamellar air enriched with oxygen with flame valence ratios of 0.7, 1.0 and 1.2, and a wide range of enrichment ratios 0 to 0.79. The study included a comparison of the thermal properties and emissions of nitrogen oxides, as well as the nature of the flame speed with an increase in the percentage of oxygen. The study showed significant differences in the oxidation process of CH_3, by significantly enhancing the reactions related to the consumption of O, OH and H. Jalil et al. [21] Presented a practical study to detect oxygen enrichment and its effect on the laminar flame speed of pre-mixed mixtures (methanol and ethanol - oxygen - nitrogen). The tube method and the optical technique (photodiode) were used to measure the velocity of the laminar flame. Through it, the positioning of the flame front was determined by the photodiode. Baigmohammadi et al. [22] noted that there was a significant effect on flame stability and location was demonstrated by using the fractionated catalyst body of the micro-reactor. Similarly, Wierzbicki et al. [23] found that the use of a catalyst significantly increased the extinction limits range and flow rates in the Swiss single-cycle combustion apparatus. With this, they note a small number of studies dealing with the property of catalytic combustion of the controllable slotted bluff body microburner. Merlo et al. [24] presented a study of combustion characteristics for turbulent swirling methane flames enriched by oxygen. From results the authors concluded there was a significant increase in flame stability and nitrogen oxides emissions. While Cardona and Amell [25] concluded that an acceleration of the laminar biogas flame occurred with an increase in the percentage of oxygen in the air.

Now, after reviewing the above-mentioned studies, many knowledge gaps are summarized as follows: The effect of oxygen enrichment on the flame behavior such as the flame temperature and the concentration of unburned fuel inside the combustion chamber which has the main factor for the generation of combustion emissions and deposits inside the combustion chamber, in addition to the effect of oxygen enrichment at flame speed.

Thus, to fill the mentioned knowledge gaps, the present study will be conducted.

In the present work, a numerical study of combustion of methane-air inside a combustor cylinder will be discussed. The effect of increasing oxygen ratio on the combustion behavior will be described. A FORTRAN-90 program based on GENMIX Spalding [26] will be developed to simulate the combustion phenomenon. CFD will be used in discretizing the governing equations.

The following paragraphs will be including the following topics: Description of the mathematical analysis of the governing equations for the combustion process; verifying the validity of the program that will be developed in this study by comparing the current numerical results with previous experimental results, and then reviewing and discussing the results of the present study and finally the conclusions that can be reached through this study.

2. MATHEMATICAL FORMULATION

In this study, the simulation of a combustion process inside a cylinder combustor will be presented numerically. The governing equations for the turbulent non-premixed combustion flame will be solved by using CFD. A FORTRAN-90 program based on GENMIX Spalding [26] will be developed. The governing equations are as follows [27]:

Mass conservation:

$$\nabla.\left(\rho\vec{V}\right)=0 \tag{1}$$

Momentum conservation:

$$\frac{\partial}{\partial x_j}\left(\rho u_j u_i-\tau_{ij}\right)=-\frac{\partial P}{\partial x_i} \tag{2}$$

where,

$$\tau_{ij}=\mu_{eff}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\mu_{eff}\frac{\partial u_k}{\partial x_k}\delta_{ij} \tag{3}$$

Energy conservation:

$$\nabla.\left(\rho u_i h\right)=\nabla.\left(k_{eff}\nabla T\right)+\frac{\partial}{\partial x_j}\left(u_i\tau_{ij}\right)+S_h \tag{4}$$

where,

$$k_{eff}=k+\frac{\mu_{eff}C_P}{Pr_t} \tag{5}$$

Species [27]:

$$\frac{\partial}{\partial x_j}\left(\rho u_j Y_i\right)=\frac{\partial}{\partial x_j}\left(\rho D\frac{\partial Y_i}{\partial x_j}\right)+M_i\omega_i \tag{6}$$

where, Y_i: is a mass fraction for mixture gas of air and methane. $M_i\omega_i$ is the mass production rate of species, and M_i is the molecular weight of i-th species, while ω_i is the reaction rate.

Turbulence model:

Turbulent kinetic energy equation [28, 29].

$$\frac{\partial}{\partial x_j}\left(\rho u_j k\right)=\frac{\partial}{\partial x_j}\left(\frac{\mu_{eff}}{\sigma_k}\frac{\partial k}{\partial x_j}\right)+G-\rho\varepsilon \tag{7}$$

where:

$$G=\sigma_{ij}\frac{\partial u_j}{\partial x_i} \tag{8}$$

Dissipation of turbulent kinetic energy equation:

$$\frac{\partial}{\partial x_j}\left(\rho u_j\varepsilon\right)=\frac{\partial}{\partial x_j}\left(\frac{\mu_{eff}}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right)+1.44\frac{\varepsilon}{k}G-1.79\rho\frac{\varepsilon^2}{k} \tag{9}$$

3. VALIDITY OF THE PRESENT CODE

In order to verify the validity of the present program, numerical results were compared with the experimental previous results of Wilkes et al. [30] for the variation of temperature along the combustor cylinder. Figure 1 represents this comparison. From this figure, there is a good agreement.

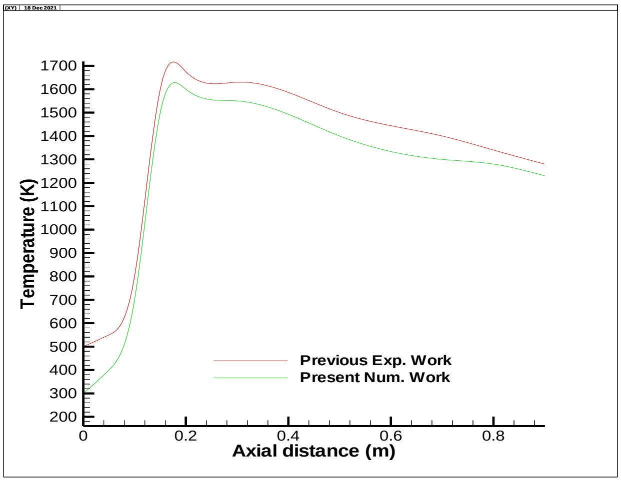


Figure 1. Comparison between present numerical results with previous experimental results of Wilkes, et al. [30]

4. RESULTS AND DISCUSSION

Through the present numerical results, the effect of oxygen ratio on the nature of combustion and on the speed of flame propagation has been studied. Figure 2 shows the temperature distribution along the axial distance of the combustion cylinder. It is noticed from the figure, that with the change in the oxygen ratio from (0.23-0.335) there is a slight change in the temperature distribution of the flame and this change becomes clearer at the oxygen ratio of 0.335 especially at the exit where a rise in temperature is observed.

Figure 3 shows the velocity contour at oxygen ratio of 0.23 and 0.335. From this figure, it can be seen that the change in oxygen ratio has no effect on the velocity profile of the burning gases.

Figure 4 shows the effect of changing the oxygen ratio on the combustion of fuel. It is noticed that the highest percentage of unburned fuel is at the beginning of the flame and decreases when moving towards the flame front and the lowest percentage is at the oxygen ratio of 0.335.

Figure 5 illustrates the distribution of air inside the combustor cylinder for the different oxygen ratios (0.23, 0.265, 0.3 and 0.335), where it is noticed from the figure that at the oxygen ratio 0.23 the air ratio inside the cylinder becomes the least possible at an axial distance of 0.78 while it is the lowest possible at an axial distance of 0.9 in relation to the oxygen ratio 0.335.

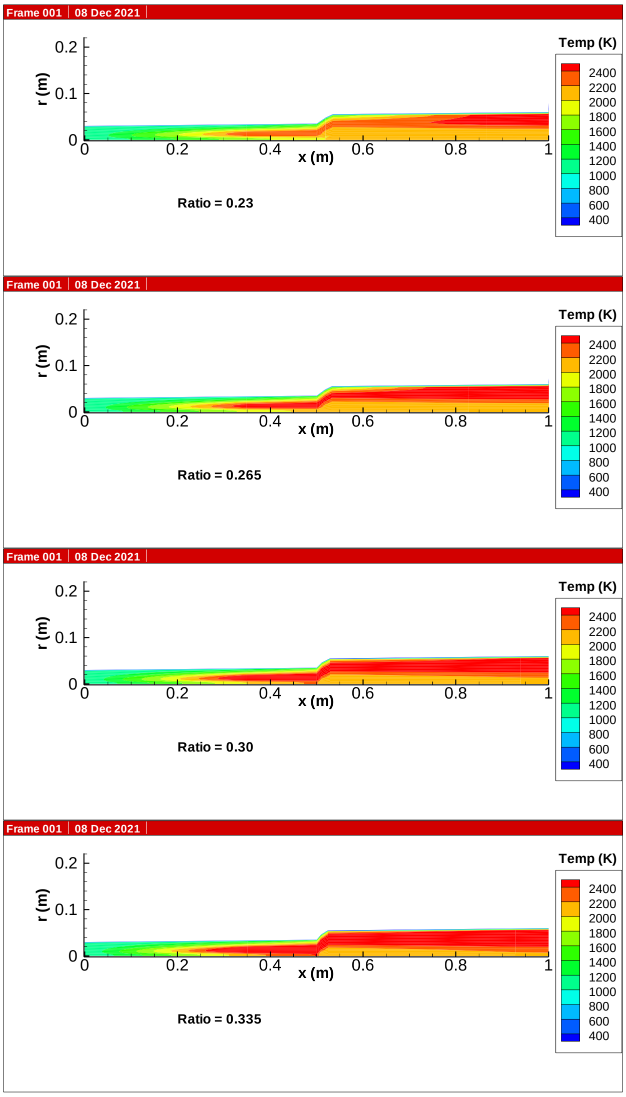


Figure 2. Temperature contour for different air ratios

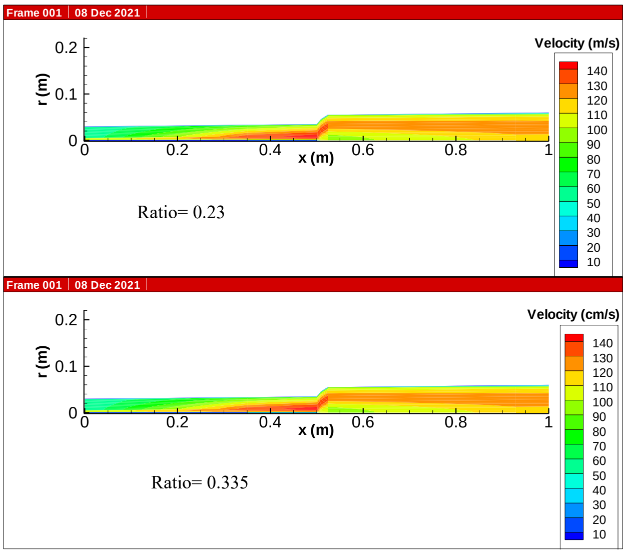


Figure 3. Velocity profile

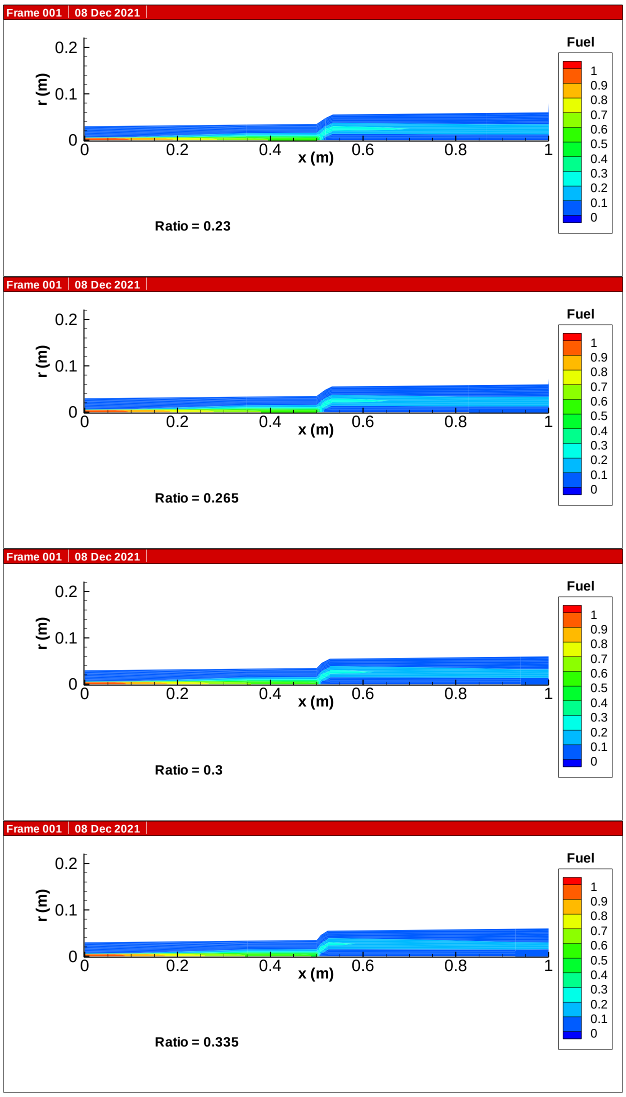
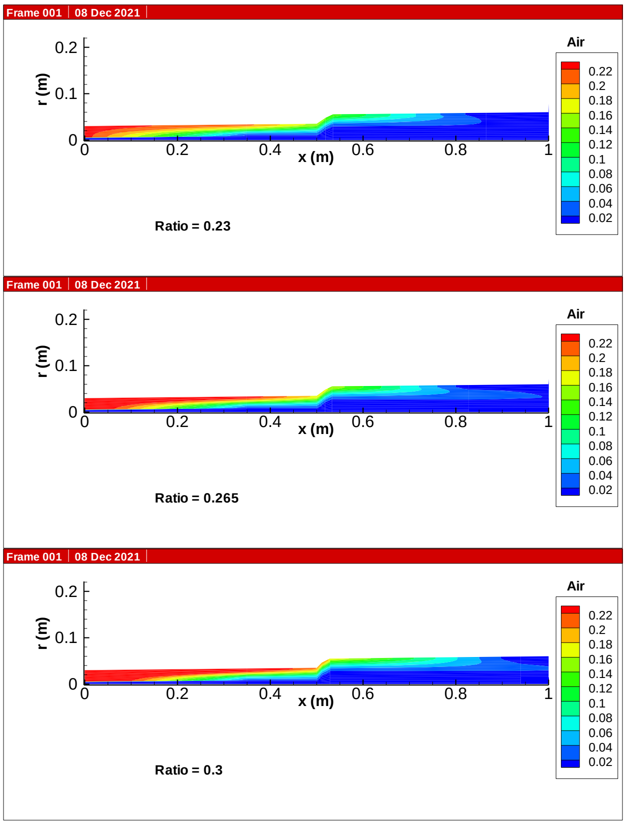


Figure 4. Unburned fuel contour



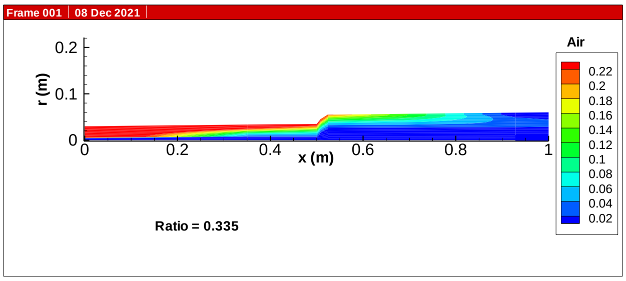


Figure 5. Air contour

5. CONCLUSIONS

The conclusions from the present study can be summarized as follows:

1. The combustion of methane-air is numerically simulated by CFD.
2. A FORTRAN-90 program was developed to simulate methane-air combustion.
3. The results showed a significant improvement in the temperature distribution inside the combustion space with an increase in oxygen ratio.
4. No effect was noticed to increase of oxygen ratio on the velocity profile inside of the flame.

With the increase in oxygen ratio, an improvement was observed in the combustion of methane.

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NOMENCLATURE

C_p	specific heat, kJ.kg^{-1}. °C^{-1}
D	hydraulic diameter, m
h	enthalpy, kJ.kg^{-1}
k	turbulent kinetic energy, m^2.s^{-3}, thermal conductivity, W.m^{-1}. °C^{-1}
P	local pressure, N.m^{-2}
Pr_t	Turbulent Prandtl number
T	temperature, °C
u	velocity components, m.s^{-1}
x	cartesian coordinate, m

Greek symbols

ε	energy dissipation rate per unit mass, m^2.s^{-3}
ρ	density of air, kg.m^{-3}
δ_{ij}	kronecker delta
μ_{eff}	effective dynamic viscosity, kg.m^{-1}.s^{-1}