4-бөлім **Раздел 4** **Section 4**

Қолданбалы математика **Прикладная математика** **Applied Mathematics**

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INFLUENCE OF THERMAL EFFECTS TO POLLUTANT DISPERSION IN IDEALIZED STREET CANYON: NUMERICAL STUDY

In this work, we numerically investigate the process of atmospheric air pollution at various values of the road temperature in idealized urban canyons. To solve this problem, the Reynolds-averaged Navier-Stokes equations (RANS) were used. Closing this system of equations required the use of various turbulent models. The verification of the mathematical model and the numerical algorithm was carried out using a test problem. The results obtained using various turbulent models were compared with experimental data and calculated data of other authors. The main problem considered in this paper is characterized as follows: estimation of emissions of pollutants between buildings using different types of hedge barriers (continuous and intermittent) at different temperatures. The results have shown that the presence of hedge barriers along the roads significantly reduces the concentration of harmful substances in the air. The use of a grass barriers with a total height of $0.1H$ leads to a decrease in the concentration level to a section $X = 0.05H$ by more than 1.5 times compared with the case of a complete absence of protective barriers. In addition, the temperature conditions (in this case, $T_H = 305K$) also reduce the concentration value by almost 2 times. Increasing the temperature at the side of the road using the barrier reduces the spread and deposition of pollutants.

Key words: Air pollution, RANS, mathematical model, hedge barriers, concentration, temperature.

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Идеалданған көше каньонындағы ластаушы заттардың дисперсиясына жылу эффектісінің әсері: Сандық зерттеу

Бұл жұмыста ауа температурасының әртүрлі мәндерінде жолдың идеализацияланған қалалық каньондарындағы ауаның ластану процесі сандық зерттелген. Бұл мәселені шешу үшін Рейнольдс орташа Навье-Стокс теңдеулері (RANS) қолданылды. Бұл теңдеулер жүйесін жабу әртүрлі турбулентті модельдерді қолдануды қажет етті. Математикалық модель мен сандық алгоритмді тексеру тест тапсырмасы жүргізілді. Әр түрлі турбулентті модельдерді қолдану арқылы алынған нәтижелер эксперименттік мәліметтермен және басқа авторлардың есептеулерімен салыстырылды. Бұл жұмыста қарастырылған негізгі міндет келесідей сипатталады: әр түрлі температура мәндерінде әр түрлі шөп кедергілерін (үздіксіз және үзіліссіз) қолдана отырып, ғимараттар арасындағы ластаушы заттардың шығарындыларын бағалау. Зерттеу нәтижелері жолдар бойында кедергілердің болуы ауадағы зиянды заттардың концентрациясын едәуір төмендететінін көрсетті.

Жалпы биіктігі 10 см болатын кедергілерді қолдану Қорғаныс кедергілерінің толық болмау жағдайымен салыстырғанда шоғырлану деңгейінің $X = 5$см қимасына дейін 1,5 есе төмендеуіне әкеледі. Сонымен қатар, температура жағдайлары (бұл жағдайда $T_H = 305K$) концентрация мәнін 2 есе азайтады. Тосқауылдың көмегімен жол жиегіндегі температураның жоғарылауы қатерлі заттардың таралуын және тұндырылуын азайтады.

Түйін сөздер: Ауаның ластануы, RANS, математикалық модель, шөптік кедергілер, концентрация, температура.

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Влияние тепловых эффектов на рассеивание загрязняющих веществ в идеализированном уличном каньоне: численное исследование

В настоящей работе численно исследован процесс загрязнения атмосферного воздуха в идеализированных городских каньонах дороги при различных значениях температуры. Для решения этой задачи использовались усредненные по Рейнольдсу уравнения Навье-Стокса (RANS). Закрытие этой системы уравнений потребовало использования различных турбулентных моделей. Верификация математической модели и численного алгоритма проводилась с использованием тестовой задачи. Результаты, полученные с использованием различных турбулентных моделей, были сопоставлены с экспериментальными данными и расчетными данными других авторов. Основная задача, рассматриваемая в данной работе, характеризуется следующим образом: оценка выбросов загрязняющих веществ между зданиями с использованием различных типов травяных барьеров (непрерывных и прерывистых) при различных значениях температуры. Результаты исследований показали, что наличие живой изгороди вдоль дорог значительно снижает концентрацию вредных веществ в воздухе. Использование живой изгороди общей высотой 10 см приводит к снижению уровня концентрации до сечения $X = 5$см более чем в 1,5 раза по сравнению со случаем полного отсутствия защитных барьеров. Кроме того, Температурные условия (в данном случае $T_H = 305K$) также снижают значение концентрации почти в 2 раза. Повышение температуры на обочине дороги с помощью барьера уменьшает распространение и отложение злокачественных веществ.

Ключевые слова: Загрязнение атмосферного воздуха, RANS, математическая модель, травяные барьеры, концентрация, температура.

1 Introduction

In large cities, air quality has been an urgent problem in recent decades, as poor air quality can worsen people's health, and the main reason is constant traffic. Most people working in large cities are more likely to go to medical institutions with complaints of problems with the respiratory system. Consequently, people with birth defects and pathologies are at risk – in this case, in addition to death, cardiovascular disorders, cancer of other serious diseases are possible [1, 2, 3]. Therefore, the search for ways to reduce the percentage of pollution along the roads is an urgent problem of mankind today. The constant increase in the number of vehicles in large cities remains the main cause of air pollution [5]. Moreover, the level of pollutants in densely populated cities increases especially strongly during certain periods [6]. To do this, there are a number of methods for reducing air pollution, such as alternative fuels and electric vehicles (EV), and solid barriers can be used to neutralize harmful substances in the air. In addition, hedges reduce noise levels by being a natural signal source, giving the city aesthetic appeal and characterizing its ecosystem services.

Various types of barriers are often used to improve air quality in urban canyons [7, 8, 9]. In addition, subsequent studies assessed the impact of protective barriers on air quality along roads [10, 11, 12, 13]. Trees [14, 15], hedges [16], green roofs and facades [17] can be protective barriers, solid barriers are also used as low boundary walls [18, 19] and noise barriers [20, 21]. The presence of parked vehicles along the road is considered to be another important factor for improving air pollution control methods, which, in turn, works like a barrier and significantly reduce the concentration of pollutants in the air [22]. Herbal barriers play a role in solving such problems; city streets reduce dispersion of pollutants [23, 24].

Vegetation barriers also reduce roadside air pollution by affecting local turbulence and the natural dispersion of pollutants generated during driving [25]. In the paper [26] indicates the best roadside safety barriers to reduce air pollution along roads in urban environments. The main purpose of using protective grasses and artisanal barriers is to mitigate the impact of pollutants by quantifying spatial changes in different pavement configurations. To determine the effectiveness of the barriers to the dispersion of pollutants into the atmosphere, CFD is used, where the barrier from natural wind flow plays the main role. The results show that obstacles increase turbulence and wind speed, and can also reduce the concentration of exhaust gases in the urban environment.

The proposed study assessed the effect of a protective barrier on the level of air pollution in an urban environment [27], taking into account the effect of temperature on the carriageway. Complex urban structures with improved infrastructure, especially during seasonal periods, such as winter seasons accumulate more heat, while in summer, on the contrary, more energy is spent for cooling than rural areas [28, 29]. All these factors affect the heat exchange of the air flow in the urban environment and lead to the urban heat island effect [30, 31]. It turned out that the value of the concentration depends not only on the total amount of malignant emissions, but also on the temperature of the walls, road and source, an analysis is required that has the following parameters: building geometry, type of pollutants and barriers, wind flow conditions, barrier porosity and temperature, which have a significant impact on urban air quality. Thus, to improve air quality, the effectiveness of two various cases of road safety barriers was evaluated various temperatures.

The main goal of this paper is to study the effect of various temperatures when using different types of protective barriers as a possible mitigation for different pavement layouts that are commonly found in the real world. The most dangerous threat to urban canyons comes from stagnant situations, that is, when a surface inversion is accompanied by a weak wind flow. All physical and mathematical assumptions were validated by computer simulations.

2 Materials and methods

2.1 Mathematical model

The system of RANS, which is simulated by the ANSYS Fluent, and used to construct a mathematical model of the flow of liquid and gas. Various RANS turbulent models were used. The implementation of the test problems was based on the existing experimental data of well-known authors. The 3D cases are presented as test problems, for which a non-stationary state model was formed to analyze the gas flow in the $L * B * H$ urban street zone.

Ethylene (C2H4) was used as a pollutant for this problem [32]. The computational model of atmospheric air pollution in the idealized urban canyon road for various temperature values based on the RANS equation, the equation for the transfer of pollutants and the energy equation.

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = \frac{\partial(-\rho\overline{u'_j u'_i})}{\partial x_j} - \frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) + f \tag{2}$$

$$\frac{\partial C}{\partial t} + \frac{\partial u_j C}{\partial x_j} = \frac{\partial(-\overline{u'_j C'})}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\gamma\frac{\partial C}{\partial x_j}\right) \tag{3}$$

$$\frac{\partial T}{\partial t} + \frac{\partial u_j T}{\partial x_j} = \frac{\partial(-\overline{u'_j T'})}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\chi\frac{\partial T}{\partial x_j}\right) \tag{4}$$

where μ is the dynamic viscosity, u_i is the velocity; P is the pressure; ρ is the density, T is the temperature, γ is the molecular diffusion coefficient, χ is the thermal diffusivity, $f = \rho g(T - T_0)$ where g is the specific force of gravity, $\overline{u'_j u'_i}$ and are Reynolds averaged velocity stresses and turbulent heat flows, respectively.

2.2 Numerical scheme

A numerical model for the presented problem was simulated by using the SIMPLE method (Semi-Implicit Method for Pressure-Linked Equations) [33-36]. This method is applied in many studies or investigations to solve many problems of hydrodynamics and heat transfer and served to create a whole class of numerical methods. All variables that were used in this simulation are completely dimensional size.

2.3 Model validation

Based on experimental studies [32], a test problem was implemented to verify the chosen mathematical model. The domain of the test problem is shown in Figure 1. The air flow rate under isothermal conditions is $V_{inlet} = 1m/s$. The tracer gas ejection rate was $3.0L/min$ using a mass flow controller. The source of the emission of the pollutant was located at the bottom center of the object under consideration and the emission velocity at the source was $V_{source} = 0.01923m/s$. The emitted contaminant was used identical to the experiment. The source line measures 0.01×0.26 meters. Similarly, to the test problem, for dimensioning, the constant $H = 1m$ will be introduced (the length of the area where the main pollution occurs). To determine the best holding abilities, several solid barriers were built with different heights $H_b = (0.05m, 0.1m, 0.2m, 0.3m$ and $0.4m)$.

As a computational grid, it was used a grid with a refinement to the center of the canyon, where the source of the ejection is located. To obtain more accurate results, high-quality grids

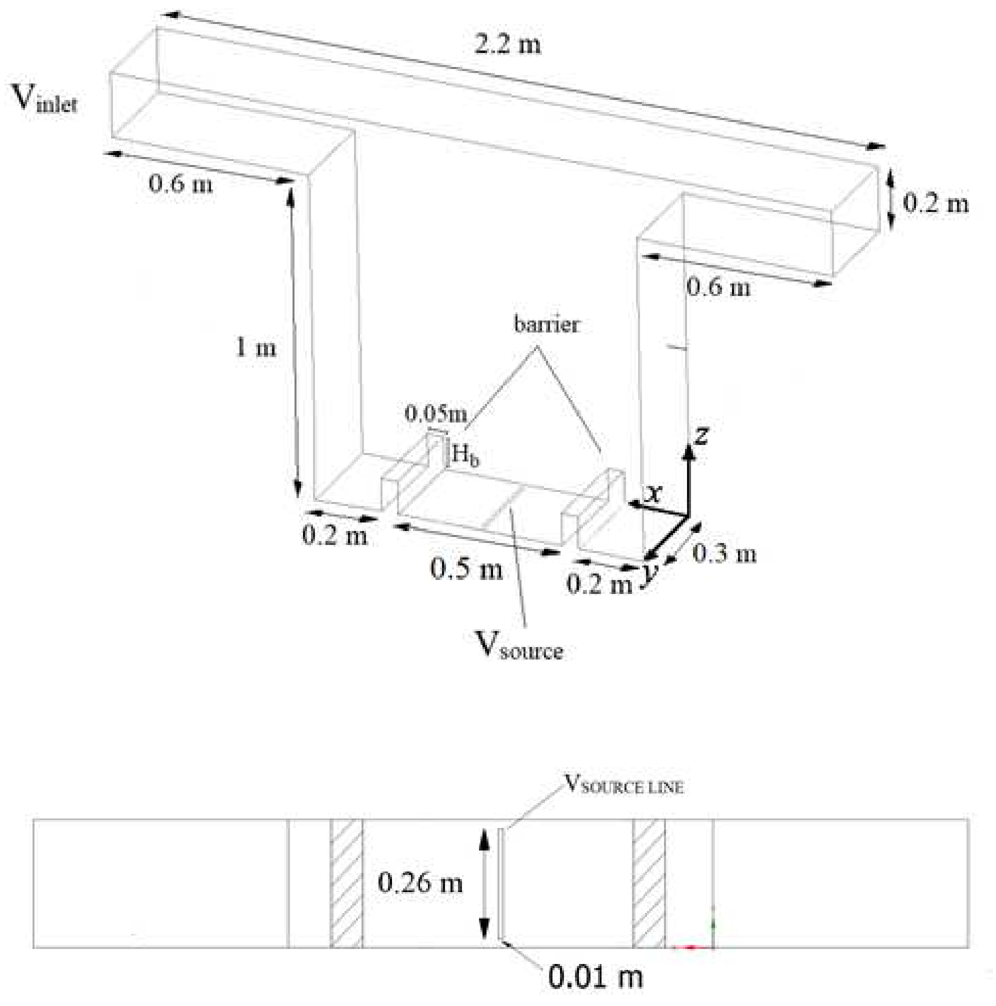

Figure 1: Test case geometry view of the cavity with herbal continuous barriers

were used in the area where velocity and kinetic energy are measured and neglected in fine grids in areas where vortex formation is not observed. As mentioned earlier, when performing the test problem, an unstructured mesh was used with a clustered to the buildings (side walls) – $0.005m$, to the surface of the earth – $0.0025m$, to the source of pollutants – $0.001m$, to the upper wall (sky) – $0.0048m$. The total number of elements and the general view of the computational grid are presented in Table 1 and Figure 2.

To simulate the test problem, the following boundary conditions were adopted, which is shown in Figure 3. The total calculation time for speed is $1800s$ with $dt = 10s$ increments.

Numerical results were compared with measurement and computational values in three control lines. For the mean velocity – exactly in the middle of the considered region in the line $x = 0.5H$, and for concentrations in three lines – $x = 0.95H$, $x = 0.5H$, $x = 0.05H$.

As seen in Figure 4, several turbulence models were used for predicting mean velocity and concentrations. From the obtained results the $k - \varepsilon$ RNG turbulence model shows the values that are closest to reality for this problem. Thus, further this turbulence model will be used

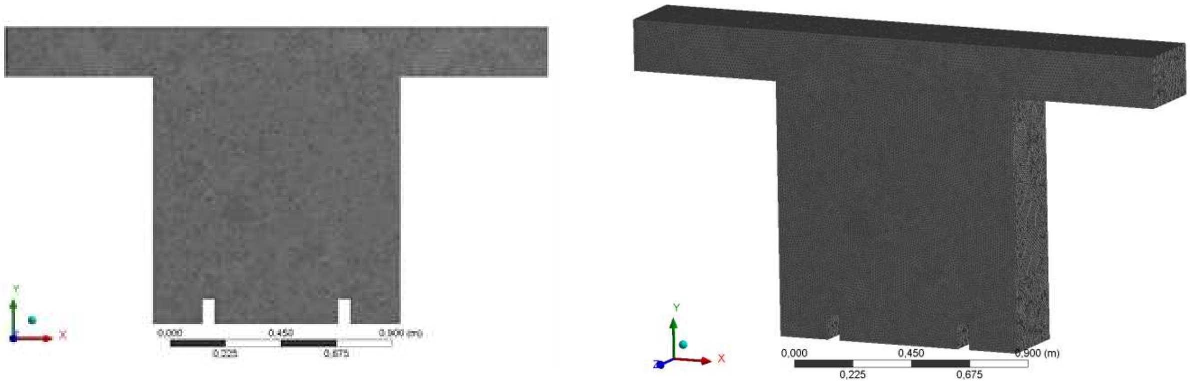

Figure 2: Computational grid

Table 1: Total number of elements and nodes for test cases

Variants of Test cases	**Elements**	**Nodes**
Without barrier	3491125	654944
Barrier 0.05 m	3033302	569837
Barrier 0.1 m	3103267	582834
Barrier 0.2 m	3242149	609064
Barrier 0.3 m	3379810	634887
Barrier 0.4 m	3519383	661186

in order to obtain computational values as close to reality as possible.

The presence of barriers with various heights significantly affects the spread of pollutants. An increase in the barrier height leads to an increase in the concentration near the source ($x = 0.5H$); however, on the opposite side ($x = 0.95H$) it noticeably decreases. As can be seen from the obtained results, a continuous type of barrier with a height of $0.05H$ and $0.1H$, the spread of the pollutant proceeds clockwise and is distributed evenly over the entire specified area. At heights of $0.2H$, $0.3H$, and $0.4H$, the nature of the movement of the pollutant changes: the direction of propagation changes in the opposite direction (counterclockwise) until reaching the height of the barrier, then the nature of the movement changes again to clockwise movement. Barriers show the ability to retain a pollutant within the source area (between barriers).

The results show that a barrier with a height of $0.1H$ has a higher contaminant retention capacity compared to a barrier height of $0.05H$. However, low height barriers (e.g. $0.05H$) offer less air flow obstacle than higher barriers (e.g. $\geq= 0.1H$) due to the unobstructed path of removal of the substance emitted from the source in the middle of the region under study. Since a barrier with a height of $0.1H$ showed the best results, which show less concentration value, it was chosen to study the effect of temperatures on the behavior of the pollutant.

Figure 6 shows the effect of different temperatures for a barrier with a height of $0.1H$. The results obtained show that an increase in temperature near the building and roads surface in the urban settings leads to an increase in pollutants in the study area. In addition, the speed of movement of the pollutant differs depending on. Temperatures $301K$ and $303K$ and without temperature show the general nature of the flow movement, and at a temperature

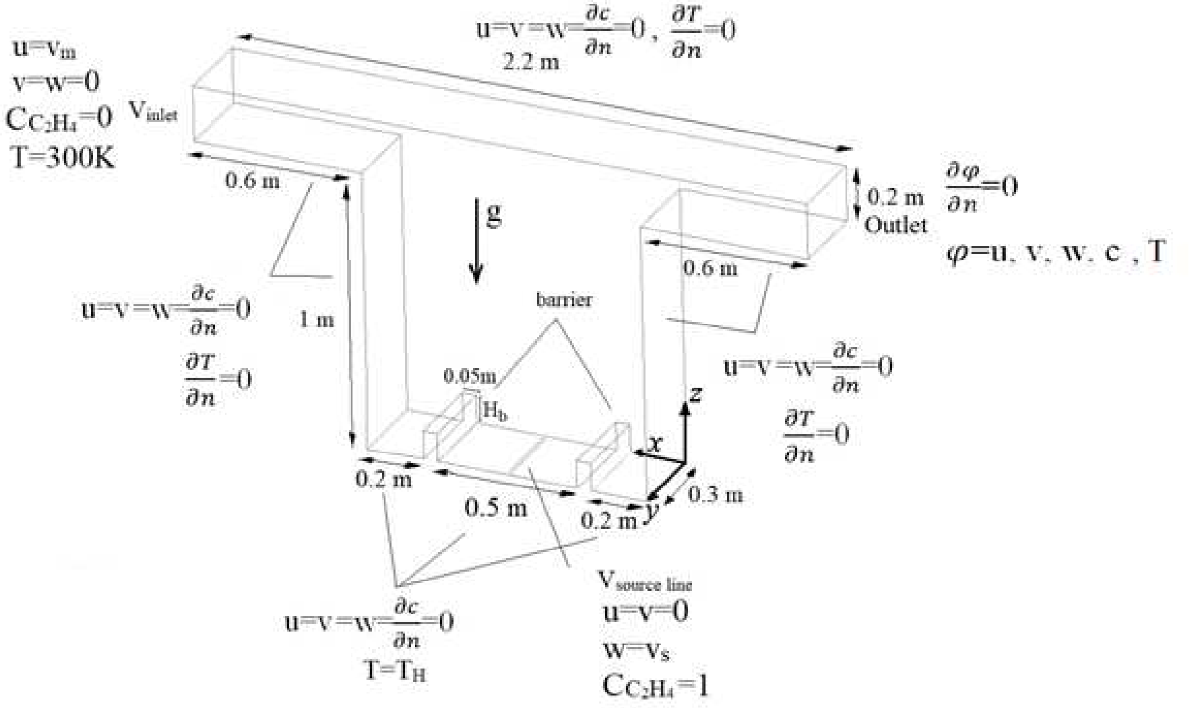

Figure 3: The schematic view of the cavity with herbal continuous barriers

of $305K$ one can see how the distribution pattern of pollutants changes in the three control lines.

3 Conclusion

In the present study, several 3D models of a street canyon were built and analyzed. After carefully studying the influence of various mathematical models on the pollutants dispersion rate, a model was chosen that showed the best results when compared with experimental values in [32]. With the help of the chosen $k-\varepsilon$ RNG turbulence model, all subsequent problems were numerically solved: an urban canyon without any internal obstacle – a barrier; a canyon with a solid barrier on either side of the pollution source. The height of $0.1H$ was chosen as the most optimal height of the barrier, as a height with the properties of simultaneous retention of pollutants from the pedestrian zone and the properties of satisfactory ventilation of the whole region. This height was applied for a continuous type of barrier when analyzing the effect of temperature on the nature of changes in the pollutant flux in a given study area.

Acknowledgements

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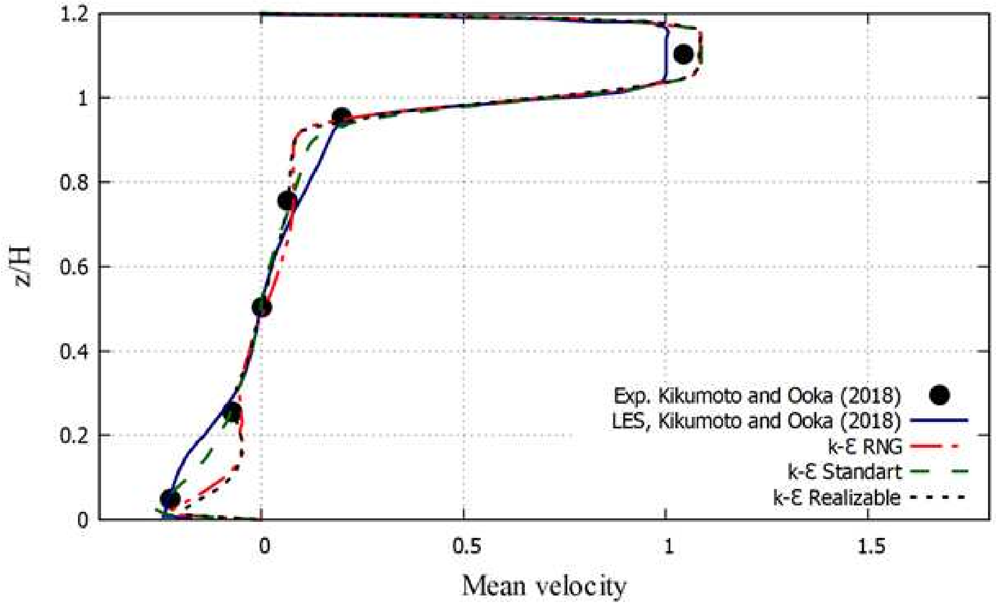
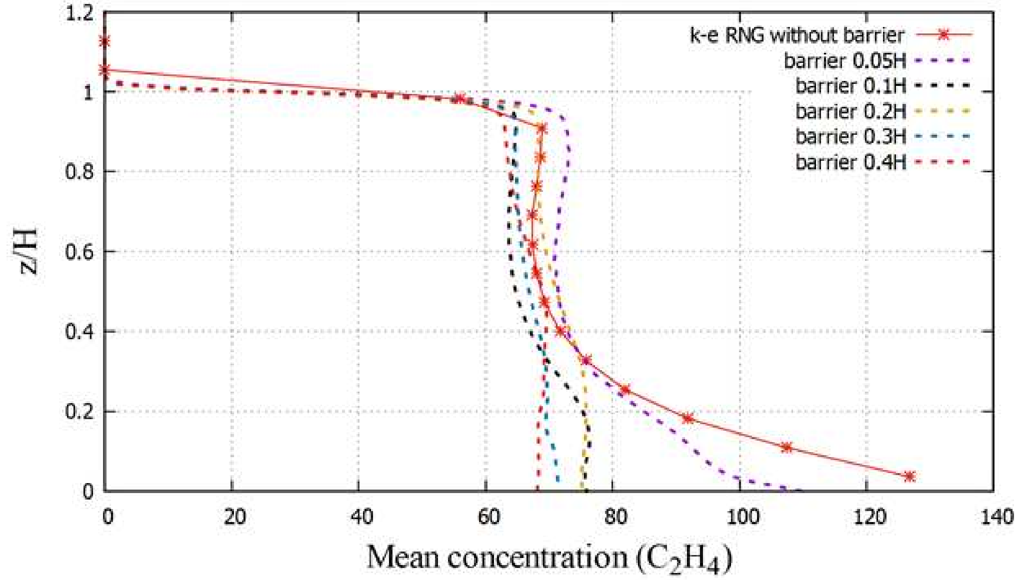


Figure 4: The mean velocity (U) profile at the $x = 0.5m$ and $y = 0.15m$ for various turbulence model



a) Line $x = 0.05H$

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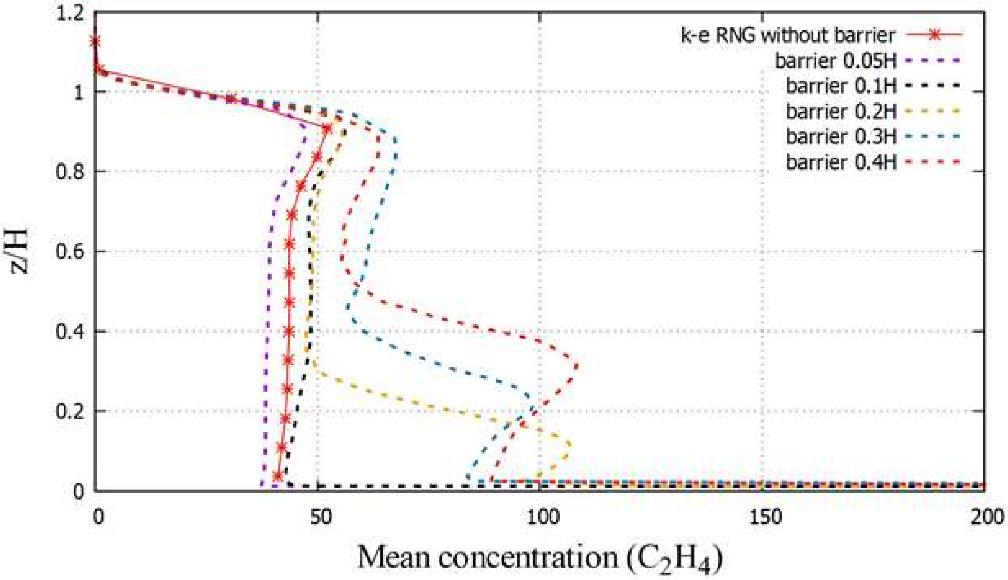
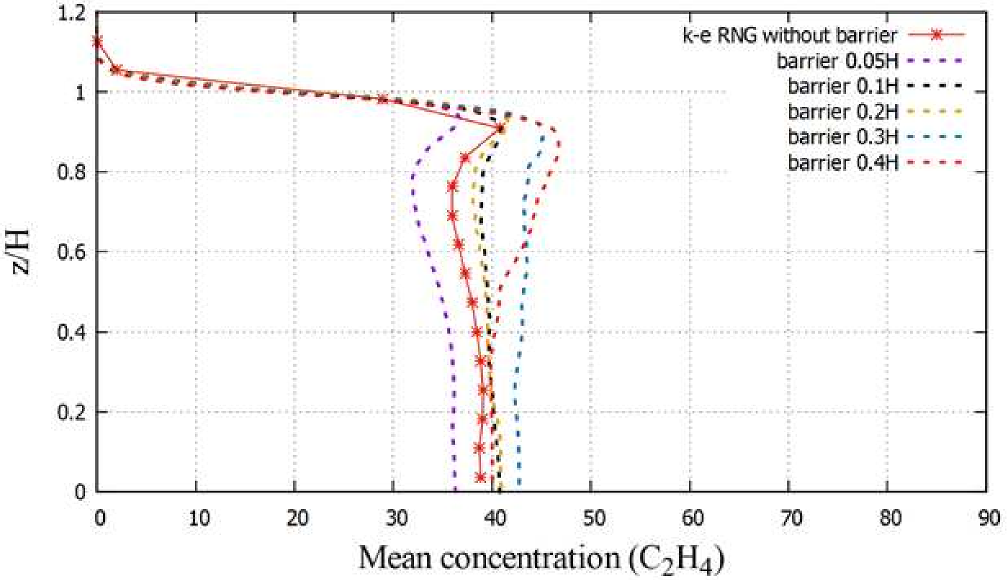


b) Line $x = 0.5H$



c) Line $x = 0.95H$

Figure 5: The mean concentration profiles without temperature

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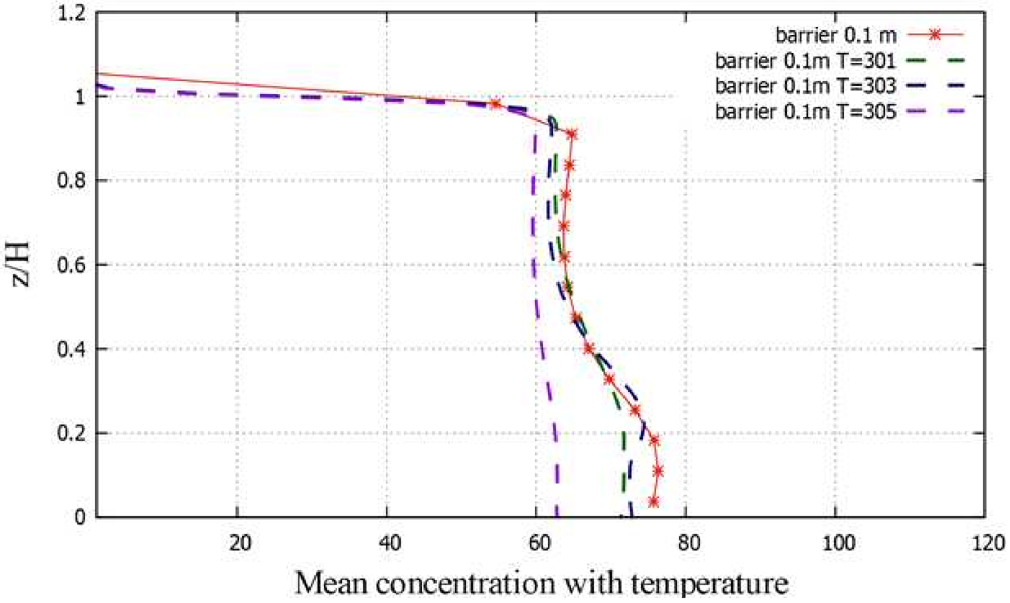
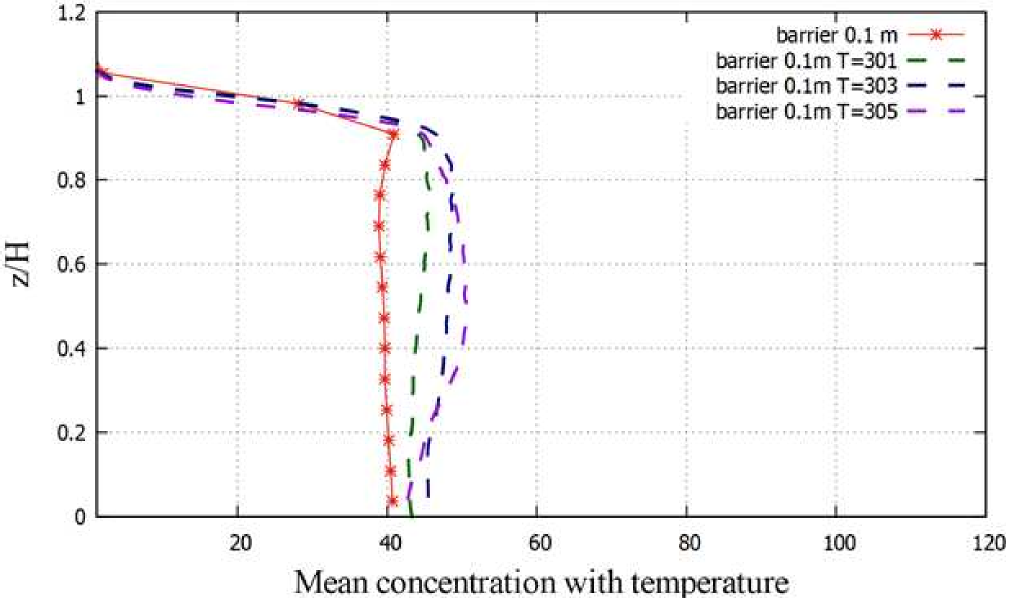


a) Line $x = 0.05H$



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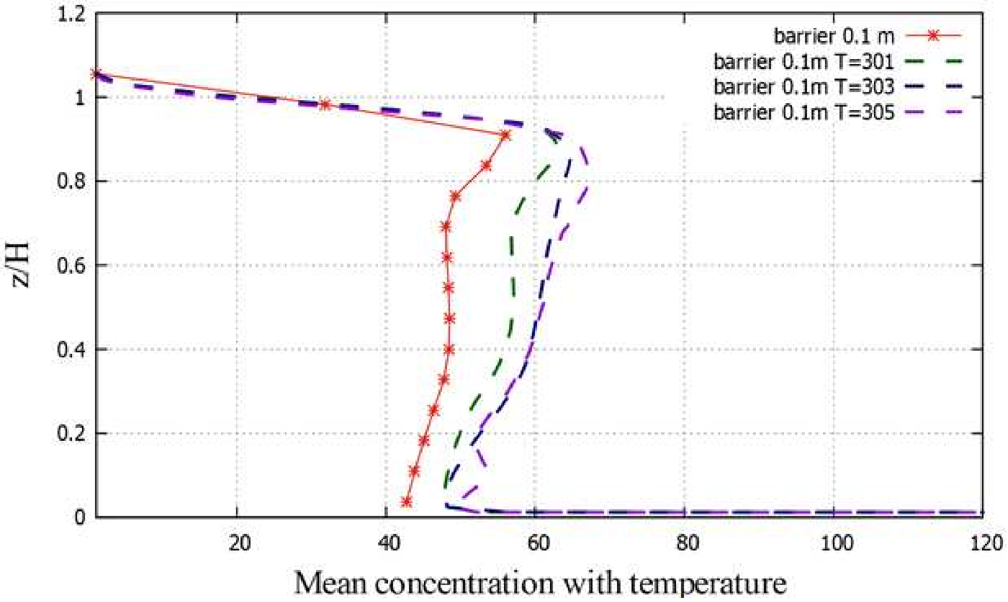

c) Line $x = 0.95H$

Figure 6: The mean concentration profiles with temperature

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