Study on Reproduction of Thermal Plume

over a Gas Stove by CFD

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In order to create a comfortable environment in the work place around commercial kitchen, it is desirable to accurately predict the capture efficiency of exhaust from the cooking appliance by CFD. Due to insufficient diffusion in buoyant plume, however capture efficiency tends to be overestimated in the k-ε model. In this study, we confirmed that the problem of the k−ε model in the prediction of plume is originated from the buoyancy production of the turbulent kinetic energy by comparing among the measurement value, simulated results using the LES model and the k−ε model, and possible remedy for discussed.

1.Background and purpose

In commercial kitchens, deterioration of the thermal and air environments due to the escape of contaminated air has becomes a significant problem. To prevent this situation, it is necessary to desig a proper ventilation system that corresponds to the exhaust gas collection rate, and computationnal fluid dynamics (CFD) is a plausible approach to predicting the hood efficiency. However, Rodi et al.[1] noted that diffusion of speed and temperature is underestimated when predicting the buoyant plume using the k−ε model for the turbulence model. Kondo et al. [2], and Kotani et al. [3] attempted to solve this ploblem by setting the distribution of measurements around the pot using CFD. However, because there are various kinds of cooking equipment, it is difficult to set the actual measured values for predicting the buoyant plume. The purpose this study is to reproduce the buoyant plume on a gas stove by applying CFD using the large eddy simulation (LES) model, comparing the results of the LES and k−ε models, and developing insights on improvethe k−ε model.

2.Comparisonof buoyant plume by CFD

2.1 Simulation summary

Rodi et al. [1] summarized their measured data on the buoyant plume and compared them to the results of the k−ε model. They noted that diffusion in the buoyant plume of the k−ε model was insufficient. The LES model is considered to have a higher preddiction accuracy than the k−ε model. So, we compared the results of k−ε and LES models with the values measured by Rodi et al.[1] using the STAR-CCM+ analysis software. Fig. 1 shows the analysis model we used for this comparison. We supplied air at low speed from the floor of the room and exhausted it at the ceiling. The boundary condition of the stove surface, was defined according to Omori's buoyant plume model.[4]. The amount of heat on the stove surface was set from the past experiment. [5]. The temperature of the stove surface was 150 °C, the blowing speed was 0.9 m/s, and the room temperature was 30 °C. Using the model shown in Fig. 1, we compared and analyzed the results of the LES and the k−ε models. We used a uniform trim mesh size of 25 mm for a total of 1.8 million mesh. A steady state analysis was performed with the standard k−ε model.
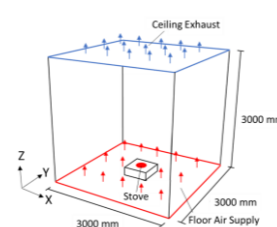

Fig.1. Analysis model for comparison of buoyant plume.

2.2 Simulation results

Based on the relationship shown in Fig. 2, Table 1 summarizes the results of the simulations S_U is the

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gradient of the half -width at half-maximum of the speed and the grade S_T of the half width at half maximum of the temperature difference. To calculate S_U and S_T, we considered nine cross sections spaced at vertical intervals of 0.25 m from 0.5 m to 2.5 m above the stove surface.
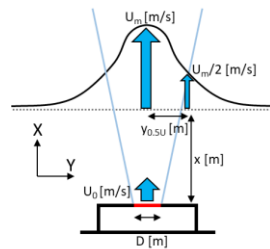

Fig. 2. Concept diagram for simulations.

Table 1. Summary of Simulation Results.

	Velocity	Temperature
Formula	$S_U = \dfrac{dy_{0.5U}}{dx}$	$S_U = \dfrac{dy_{0.5T}}{dx}$
k−ε(Rodi)	0.079	0.076
experimental recommendation (Rodi)	0.112	0.104
k−ε (STAR-CCM+)	0.071	0.067
LES (STAR-CCM+)	0.115	0.091

In the k−ε model, the results for both the speed and temperature difference indicated significant diffusion deficiencies. On the other hand, the LES model were close to the experimental recommendations of Rodi et al., and we confirmed that the resulta of this analysis were highly reproducible. Equation (1) states that the rate of change of the turbulent kinetic energy (k) is balanced by a number of physical processes.

$$\frac{\partial k}{\partial t} = \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j} - kU_j\right] + P_k + G_k - \varepsilon \qquad (1)$$

where P_k is the production of turbulent energy due to Reynolds stress and G_k is the production of turbulent energy due to buoyancy. Figs. 3, 4, and 5 are comparisons of k, P_k, and G_k respectively. The values of CFD analysis were simulated at 1 m above the stove surface, and the calculated values (based on Rodi et al) assumed a pure plume. The charts show that the calculated values and the LES model results correspond to the transition away from the central axis. Rodi et al. stated that the ratio of the calculated P_k to G_k is 3:1. In the LES model, the ratio of P_k to G_k was 2.8 at y /$y_{0.5U}$ = 1 (the full-width at half-maximum). This value corresponds to the value of Rodi et al. . Fig. 5 shows that buoyancy (represented by G_k) made little consideration in the k-ε model.
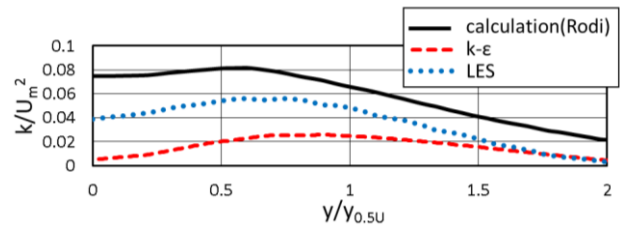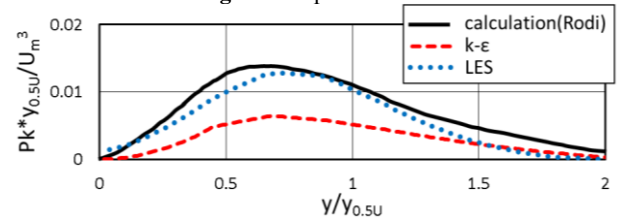

Fig. 3. Comparison of k.

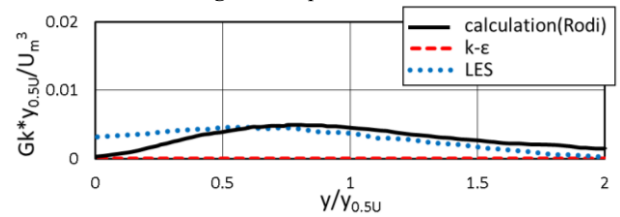**Fig. 4.** Comparison of P_k.

Fig. 5. Comparison of G_k.

3.Reproduction of stove model

3.1 Analysis summary

Fig. 6 shows another version of the analysis model is with a pot placed on the stove model described in Section 2. The boundary conditions of the pan surface and the stove were defined according to Omori's combustion waste airflow model.[4] The amount of heat on the stove surface and the amount of steam generated on the upper side of the pot were set to correspond to the previous experiment.[5] Using the model shown in Fig. 6, we compared and analyzed the analysis results of the LES and the k−ε models. We used a uniform trim mesh size of 25 mm for a total of 1.72 million mesh elements over the whole domain. A stationary analysis was performed with the standard k−ε model.
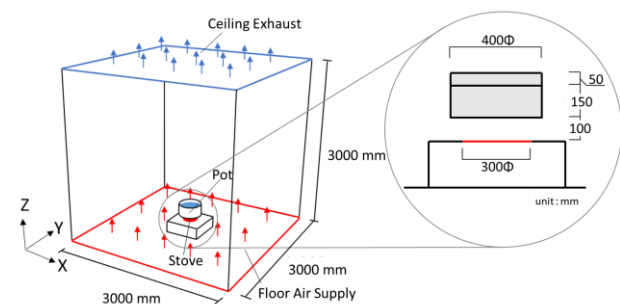

Fig. 6. Analysis model for comparison of buoyant plume.

3.1 Simulation result

Fig. 7 shows the velocity distributions in the vertical direction, and Fig. 8 shows the temperature distributions at the height of 1000 mm from the bottom of the pot .The temperature distributions show the temperature differences relative to the room temperature of 30 ℃. The time average between 100 s and 200 s after the start of the calculation was used in the LES model.
Q_{plm} is defined in Equation (2), as follows :

$$Q_{plm} = \int_0^{r_{plm}} 2\pi r \rho c_p \hat{w}\hat{t}\,dr \qquad (2)$$

where $\hat{w}$ is the velocity in the vertical direction, $\hat{t}$ is temperature difference relative to the room temperature, ρ is the density, and c_p is the specific heat at constant pressure.The integration is performed from the central axis to the outer edge (r_{plm}) of the heat-convecting airflow.The time average of Q_{plm} is expressed by Equation (3) by using Equation (4), as follows :

$$\overline{Q_{plm}} = \int_0^{r_{plm}} 2\pi r c_p WT\,dr + \int_0^{r_{plm}} 2\pi r \rho c_p \overline{wt}\,dr \qquad (3)$$

$$\overline{\hat{w}\hat{t}} = WT + \overline{wt} \qquad (4)$$

In the analysis with the LES model, we found that the second term on the right-hide of the Equation (3) was approximately 10% of Q_{plm}. Therefore, the calorific heat value that was used in this analysis ignored the turbulent heat flux represented by the second term on the right-hide of the Equation (3). Thus, the temperature distribution from the experiment was calculated using only the average flow field due to the heat flux represented by the first term on the right-hide of Equation (3). In addition, the temperature distribution was assumed to be similar to the vertical velocity distribution.
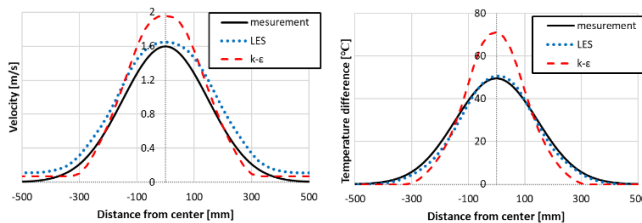

Fig. 7. Velocity distributions.

Fig. 8. Temperature distributions.

The temperature and speed on central axis obtained from the k−ε model were higher than the corresponding measured values. We attributed this observation to insufficient diffusion in the model, as compared to the actual plume. On the other hand, the results from the LES model were close to the actual measurements. Figs. 9 and 10 compare the vertical speed and temperature contours, respectively, from the LES and k−ε models. Since the value the k−ε model shows large values on the central axes, we determined that the k−ε model had much less diffusion than the LES model.
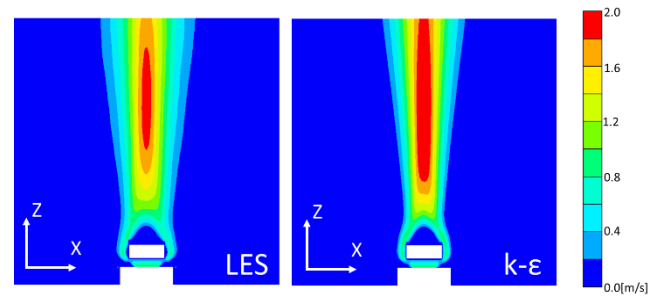

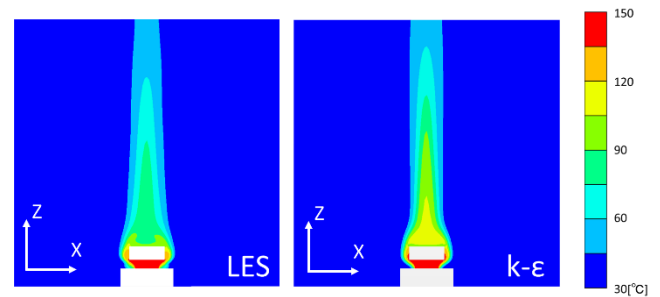**Fig. 9.** Vertical speed contours from model results.

Fig. 10. Temperature contours from model results.

Fig. 11 shows the contours of k.In the LES model, the turbulent energy is calculated using Equation (5).

$$k = \frac{\overline{u_1^2} + \overline{u_2^2} + \overline{u_3^2}}{2} \qquad (5)$$

Similar to Figs. 9 and 10, the contours in Fig. 11 indicate higher diffusion in the LES model. An increase in k causes an increase in turbulent diffusion. Therefore, we setermined that k caused increase in temperature and vertical speed.
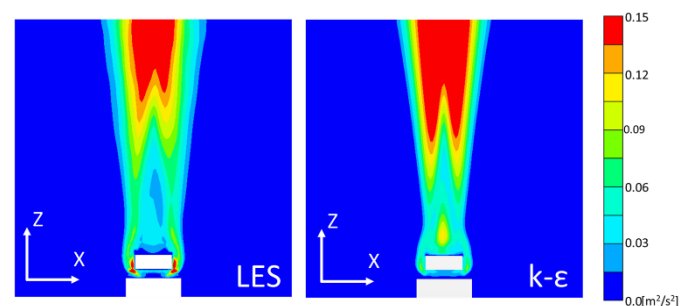

Fig. 11. Contours of k from model results.

G_k, the production of turbulent energy due to buoyancy was calculated by the Equation (6), as follows :

$$G_k = -\beta g_j \overline{\theta u_j} \qquad (6)$$

where β is the thermal expansion coefficient, g is the gravitational acceleration, and $\overline{\theta u_j}$ is the turbulent heat flux.

In the LES model, $\overline{\theta u_j}$ was calculated using Equation (4), but in k−ε model, it was calculated using Equation (7), as follows :

$$\overline{\theta u_j} = -\frac{v_t}{P_{rt}}\frac{\partial \Theta}{\partial X_j} \tag{7}$$

where v_t is the vertical viscosity coefficient and P_{rt} is the turbulent Prandtl number.

P_k, the production of turbulent energy due to Reynolds stress, was calculated by the Equation (8), as follows :

$$P_k = -\overline{u_i u_j}\frac{\partial U_i}{\partial X_j} \tag{8}$$

In the LES model, the Reynolds stress was estimated using Equation (4), whereas in the k−ε model, it is calculated using Equation (9) , as follows :

$$-\overline{u_i u_j} = v_t\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_i}{\partial X_j}\right) - \frac{2}{3}\delta_{ij}k \tag{9}$$

where δ_{ij} is one when i = j and zero when i ≠ j. Fig. 12 shows the contours of P_k, which indicate little difference in the distribution between the LES and k−ε models. The contours of G_k, as shown Fig. 13, indicate large positive contributions in the LES model, but almost none in the k−ε model. In the k−ε model, gradient diffusion approximation was used to turbulent heat flux in the vertical direction. Thus, we determined that ∂θ/∂Z in Equation (7) was approximately zero.
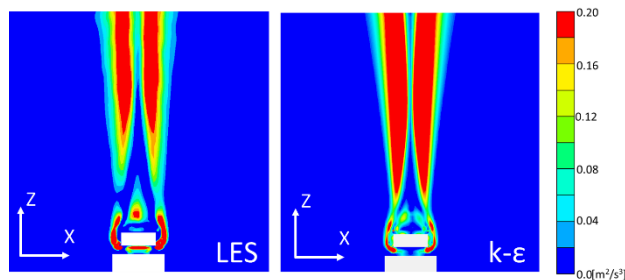

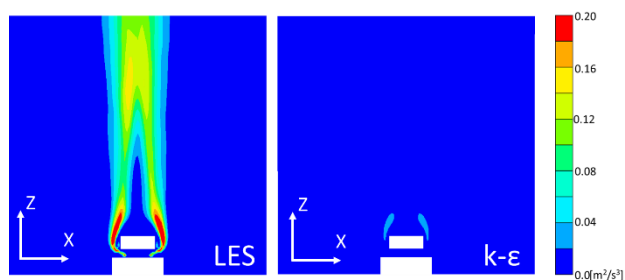**Fig. 12.** Contours of P_k from model results.

Fig. 13. Contours of G_k from model results.

Conclusions

The following findings were obtained from this study:
1) The LES model is more diffusive than the k−ε model; thus, it is possible to improve the stove model and consequently obtain a better the measured airflow.
2) The extremely small value of G_k in the k−ε model could be one reason why this model performs poorly in reproducing the heat-convecting air current.
3) Future studies would include increasing the prediction accuracy of G_k and incorporating G_k into RANS.

Reference

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