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A Flow Analysis of a Refrigeration Warehouse where an Unusual Death of an Operator Occurred by Deficiency of Oxygen

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Abstract: A numerical flow analysis of the case of a refrigeration warehouse where an unusual death of an operator occurred by deficiency of oxygen is performed by using STAR-CD program of the computational fluid dynamics (CFD) code. The refrigeration room of the warehouse for storing the fruits maintains an atmosphere of 95% nitrogen and 5% oxygen by volume. When the operator was found dead in the refrigeration room, the room was in normal operating conditions except for the fact that the auxiliary door had been left open. For the flow analysis, unsteady 3-dimensional natural convection with mass transfer is considered. The flow analysis result is compared with the oxygen concentration level measured against time during on-site investigation. The change in oxygen concentration level in the warehouse due to the opening of the auxiliary door is found to be negligible.

Keywords : computational fluid dynamics, flow analysis, oxygen, refrigeration warehouse, STAR-CD

Nomenclature

C_m	Concentration of species m	D	Binary diffusion coefficient
h	Refrigeration room height	g	Gravitational acceleration
Gr	Grashof number	k_f	Thermal conductivity
Pr	Prandtl number	Ra	Rayleigh number
Sc	Schmidt number	T	Temperature
u_i	Velocity component(u, v, w)		
Greek symbols			
α	Thermal diffusivity	ε	Dissipation of turbulent kinetic energy
κ	Turbulent kinetic energy	μ	Coefficient of viscosity
μ_t	Coefficient of turbulent viscosity	ρ	Density
$ó_t$	Turbulent Prandtl number for T	σ_κ	Turbulent Prandtl number for κ
σ_t	Turbulent Prandtl number for ε	σ_c	Turbulent Prandtl number for C_m
ν	Kinematic viscosity		
Abbreviations			
refri	Refrigeration room	corri	Corridor

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1. Introduction

The unusual death of the operator at the fruit warehouse occurred on 3 March 2003. The warehouse consists of refrigeration rooms and maintenance corridor. The refrigeration room has a main door and auxiliary door for entrance from the corridor. Ambient air conditions are maintained in the corridor. The refrigeration room stores fruits by using nitrogen gas at low temperature. The normal operating conditions are shown in Table 1. Schematic view of warehouse is shown in Fig. 1. He was found in the refrigeration room at a distance of 2m from the opened auxiliary door. It was reported that the characteristic evidence indicating murder or sickness were not found[1, 2]. At the site investigation, we measured oxygen concentration in the refrigeration room with the conditions of the warehouse similar to when he was found and concluded that he died from the deficiency of oxygen in the refrigeration room.

In this work, we numerically study the flow of warehouse by using STAR-CD program to investigate overall flow patterns. The analytical results are compared with the measured oxygen concentration against time at the site investigation.

We receive many unusual deaths from poisoning from toxic gases, deficiency of oxygen and from suffocation by smoke. The need for an overall flow analysis is increased because site measurements limited dot not always have the overall aspects of the site conditions. The objectives of this work are to analyze the warehouse accident, verify effectiveness of flow analysis for the science investigation and provide suggestions to prevent reocurrence.

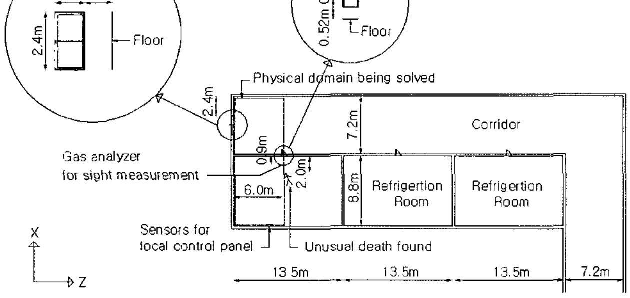

Fig. 1. The schematic view of warehouse.

Table 1. The normal operating conditions of refrigeration room.

Temperature	0~5°C
Humidity	88100%
Oxygen concentration	1~5% Volume
Nitrogen concentration	95~99% Volume
Pressure	Atmospheric pressure

2. Site measurements and numerical analysis

2.1 Site measurements

At site investigation, we set the operating conditions of the refrigeration room similar, but not exactly, as when the as unusual death was found because of limited site operating conditions of refrigeration room. The refrigeration room is initially filled with approx. 90% volume nitrogen and 10% volume oxygen. The temperature is maintained at 5°C at atmospheric pressure. No other nitrogen gases are filled when the steady state is reached. The operating conditions of the refrigeration room are monitored at the local control panel of the warehouse which indicates humidity, temperature and the concentrations of nitrogen gas and oxygen gas. The sensors for local control panel are installed in the inner wall of refrigeration room opposite across the room from the auxiliary door. An additional gas analyzer is installed in the refrigeration room near the auxiliary door for oxygen concentration measurement at site investigation. The temperature of corridor is measured at approx. 20°C. When the operating conditions of refrigeration room reach steady state, the auxiliary door is opened and the transient conditions of refrigeration room are measured for approx. 15 minutes at both the local control panel and the gas analyzer.

2.2 Numerical analysis

Unsteady 3-dimensional natural convection with mass transfer is considered. To solve the oxygen concentration with time, air at the corridor is assumed to be a mixture of 79.05% nitrogen by volume and 20.95% oxygen by volume with a temperature of 20°C. The initial conditions of refrigeration room are set to the conditions of site measurement with a mixture of 90% nitrogen by volume and 10% oxygen by volume with a temperature of 5°C to compare with results of site measurement. The temperature dependence of mass diffusion is considered by using the binary diffusion coefficient between oxygen and nitrogen assuming ideal gas behavior[3]. The Schmidt number indicating the ratio of the momentum to mass diffusivities is as follows;

$$Sc = \frac{\upsilon}{D_{N_2O_2}} = 0.76 \quad (1)$$

General form of the Grashof number indicating the ratio of the buoyancy force to the viscous force acting on binary mixture is as follows;

$$Gr_h = \frac{g(\Delta\rho/\rho)h^3}{\upsilon^2} = \frac{g(\rho_{refri}-\rho_{corri})h^3}{\rho\upsilon^2} = 3.79\times10^{11} \quad (2)$$

where $\rho = \frac{\rho_{refri}+\rho_{corri}}{2}$.

The Rayleigh number, the product of the Prandtl and Grashof number, is calculated as follows;

$$Ra = Pr\times Gr_h = \frac{(\rho_{refri}-\rho_{corri})}{\rho}\frac{h^3}{\alpha\upsilon} = 2.73\times10^{11} \quad (3)$$

The properties for the Schmidt, Grashof and Rayleigh numbers are calculated by considering mass-weighted averages for the property condition of each refrigeration room and corridor.

Turbulent flow is considered because Rayleigh numbers less than 10^8 usually indicate laminar flow, with the onset of turbulence occurring over the range $10^8 < Ra < 10^{10}$[4,5]. It is reported that simulation of mixed convection in a room air flow with a two-layer turbulence model has more accurate results than standard k-ε model[6]. The two layer turbulence model applies the standard k-ε model equations everywhere except the viscous-influenced, near-wall flow region where a low Reynolds number representation of the turbulence equation is used. It is reported that a two-layer turbulence model is useful for rooms with heated sources and cooled surfaces. But in this calculation, natural convection in the form of a plume is expected without heated or cooled surface, so the standard k-ε model is used for convenience.

The governing equations in the tensor form are as follows:

Continuity Equation

$$\frac{\partial}{\partial t}(\rho)+\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (4)$$

Momentum Equation

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_i}(\rho u_j u_i) = -\frac{\partial p}{\partial x_i}+g_i(\rho-\rho_{corri}) + \frac{\partial}{\partial x_j}\left[(\mu+\mu_t)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\kappa\delta_{ij}\right] \quad (5)$$

Energy Equation

$$\frac{\partial}{\partial t}(\rho t)+\frac{\partial}{\partial x_j}(\rho u_j T) = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu_t}{\sigma_t}+\frac{k_f}{C_p}\right)\frac{\partial T}{\partial x_j}\right] \quad (6)$$

Species Continuity Equation

$$\frac{\partial}{\partial t}(\rho C_m)+\frac{\partial}{\partial x_j}(\rho u_j C_m) = \frac{\partial}{\partial x_j}\left[\left(\rho D+\frac{\mu_t}{\sigma_c}\right)\frac{\partial C_m}{\partial x_j}\right] \quad (7)$$

Turbulent Equation(Standard κ-ε)

$$\frac{\partial}{\partial t}(\rho\kappa)+\frac{\partial}{\partial x_j}(\rho u_j\kappa) = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\kappa}\right)\frac{\partial\kappa}{\partial x_j}\right]+G-\rho\varepsilon \quad (8)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho u_j\varepsilon) = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\kappa}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\frac{\varepsilon}{\kappa}(C_1G-C_2\rho\varepsilon) \quad (9)$$

where, the coefficient, source term and turbulent constants used in the governing equations are as follows:

$$\mu_t = \rho C_\mu\frac{\kappa^2}{\varepsilon},\ G=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j},\ C_1=1.44, C_2=1.92,$$
$$C_\mu=0.09,\ \sigma_t=0.85,\ \sigma_\kappa=1.0,\ \sigma_\varepsilon=1.3,\ \sigma_c=0.9$$

For simplicity and saving computing time, a symmetric configuration for the warehouse is chosen. The centerline of the auxiliary door is approx. equal to the centerline of the refrigeration room. The unsteady numerical calculation is performed until the returning flow from the corridor wall affects the flow conditions at the auxiliary door. No slip and adiabatic conditions are chosen at the wall.

The pressure field at each cell was calculated by SIMPLE algorithm and the convection term was determined by MAR(Monotone Advection and Reconstruction) scheme[5]. Preliminary unsteady 2-dimensional numerical calculation was performed to verify the mesh size and the time step. A non-uniform mesh of 968,660 cells with mesh sizes of 5.5~13 cm was used. The time step was 0.01 second.

3. Results and Discussion

The change of oxygen concentration measured at the entrance of the auxiliary door by the gas analyzer was negligible. After a period of 15 minutes, the oxygen concentration only changed from approx. 10% volume to 10.4% volume. Similar results are recorded at the local control panel, which has a sensor installed at the opposite side of auxiliary door.

Fig. 2 to Fig. 4 shows the calculated velocity field, temperature field and oxygen concentration field in the warehouse at 5 seconds, 20 seconds and 50 seconds. The calculated flow from the refrigeration room through the auxiliary door reaches the corridor wall opposite to the symmetric plane at approx. 50 seconds where the calculation is stopped. It shows that the flow is primarily initiated by natural convection. The flow in the refrigeration room shows traditional free boundary flow in the form of a plume[4]. The air from the corridor rises due to buoyancy forces, as entraining quiescent gases of refrigeration room. Buoyancy-driven free boundary layer flow is developed up to the ceiling. The free boundary layer flow bounces and moves along the ceiling without moving downward because of buoyancy effect. The temperature and oxygen concentration field are strongly affected by natural convection. This shows that mass transfer from the corridor strictly changes the oxygen concentration close to the ceiling only. This explains why the oxygen concentration change near the auxiliary door is negligible.

The reverse phenomenon is shown at the flow field of the corridor. The gases from refrigeration room moves downward to the corridor floor because of gravity and spread along the floor. There is a sliding type window at the end of the corridor wall opposite to the symmetric plane of the auxiliary door. Its dimensions are 2.4 m ×1.2 m and 1.1 m higher from the floor. Judging from this computation results, it will have little effect on ventilation. It is recommended that the installation of a sash type window possibly near the floor is more appropriate

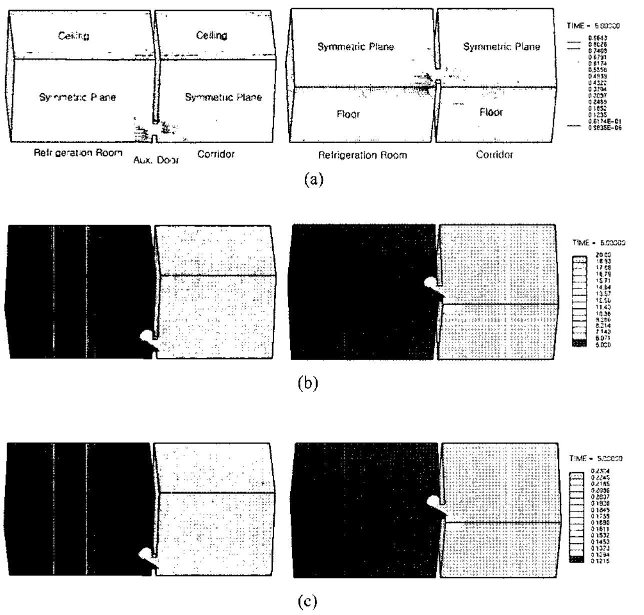

Fig. 2. The calculated flow field of warehouse at 5seconds, (a) Velocity field(m/s), (b) Temperature field(°C) (c) Oxygen mass concentration field.

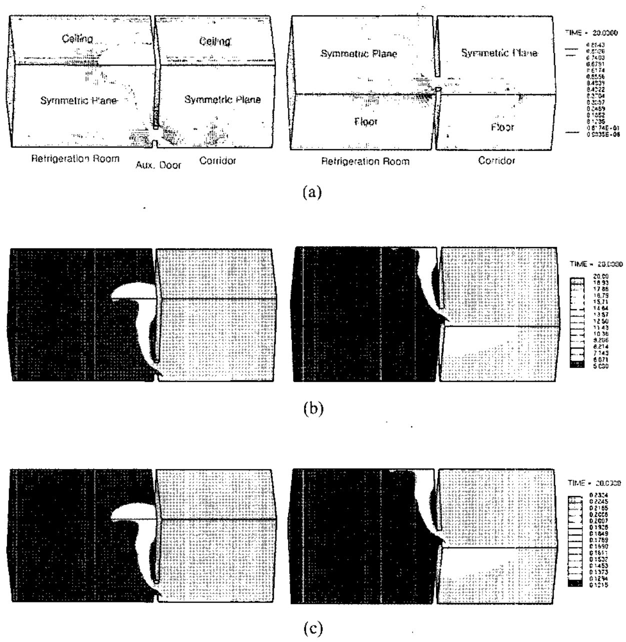

Fig. 3. The calculated flow field of warehouse at 20seconds, (a) Velocity field(m/s), (b) Temperature field(°C) (c) Oxygen mass concentration field.

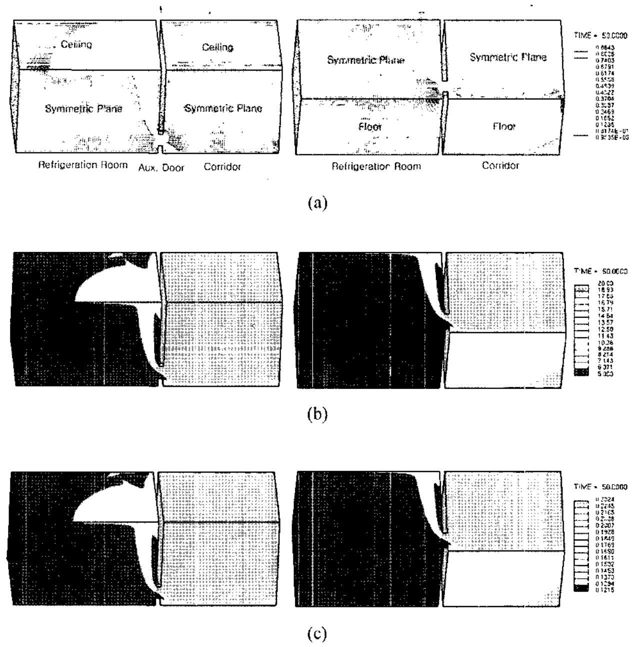

Fig. 4. The calculated flow field of warehouse at 50seconds, (a) Velocity field(m/s), (b) Temperature field(°C) (c) Oxygen mass concentration field.

for the corridor wall considering ventilation effect at maintenance etc.

4. Conclusions

The air flow pattern of a refrigeration warehouse where an unusual death of an operator has occurred was numerically studied by using STAR-CD program of the CFD code. The calculated results show that the air flow in the refrigeration room forms a free boundary flow of the plume type when the auxiliary door is left opened. When the air flow reaches the ceiling, it moves along the ceiling and does not rapidly move downward. The temperature field and the oxygen concentration field are strongly affected by the free boundary flow of the plume type. As a result, the oxygen concentration in the refrigeration room near the floor does not easily change whether the auxiliary door is left open or closed. This explains why the measured oxygen concentration level did not change much during on-site investigation. It can be concluded that the dead operator was negligent when he addressed the danger of the oxygen deficiency by opening the auxiliary door only.

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