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Dynamic simulation of contaminant inleakage produced by human walking into control room

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A B S T R A C T

Human walking-induced transport can be a significant mechanism during entry from a contaminated region into a protective enclosure, such as a control room. The passage through the door gives the outside air the opportunity to leak into the control room, endangering the staff inside. The objective of this study is to simulate contaminant transport induced by human walking motion in simplified situations – the person moving from the corridor into the anteroom, with various entrance times (from 2 to 8 s). The CFD simulations were made by using the RANS solver with dynamic meshes techniques. The inleakage airflow through the doorway and the inleakage air volume can be both quantified with tracer gas measurements. The simulation results illustrated that the whole inleakage process can be divided into four stages: door draws in air; person entrains the air; door closing cuts short the wake; and door pushes the air in the final movement. It was found that the total inleakage volume is affected by the entrance time, and can be as much as 1.192 m^3 for an 8.0 s entrance time. The data measured in our previous experimental study were employed to validate with the simulation result. The comparison result indicated an agreement when the entrance time was 3–8 s, but as the entrance time increased, the simulation values were significantly higher than those measured experimentally. The simulation results can therefore be considered as a conservative estimate, which can guide the prevention of inleakage in future engineering applications.

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1. Introduction

A control room (CR) is a key place for the nuclear power plant, from which actions are taken to operate the plant safely under normal conditions and to maintain the reactor during accident situations. When the accident occurs, the operators are the most important role to save the plants from a nuclear disaster, so they must remain in the control room for at least 72 h to shut down the reactor completely. Therefore, it is necessary to provide a safe indoor environment all the time, in order to protect the personnel from the radioactive and contaminant exposure, especially during the accidents [1].

The most important source of hazardous exposure that jeopardizes the personnel safety is the contaminated air inleakage from the adjacent corridor into the control room. This inleakage can occur when a person walks into the CR, potentially carrying or inducing the radioactive contaminated gas into the CR. The "inleakage" emphasizes the flow direction. It is from corridor into the CR that unfiltered air disperses [2]. The inleakage volume only counts the air that enters the CR from corridor and remains inside. This paper did not intend to find which kind of contaminants would transfer into the control room, and how their distributions were outside the control room. Instead, we focused on the inleakage volume. It is the inleakage air that contains all the contaminants and endangers personnel safety. Therefore, to guarantee the indoor environment, first of all, the inleakage volume should be restricted and determined. No matter how much contaminants the inleakage air carries, this unfiltered air in accidents is considered as 100% dangerous.

Some reports and regulations reflect that the major inleakage pathway for the control room is the person entering and exiting through the entrance door [3,4]. They also suggest a typical inleakage flowrate estimation for the control room safety analysis, as 17.0 m^3/h for a control without a vestibule, or 8.5 m^3/h for a control room with a vestibule [2]. Many control rooms have applied this estimation for safety assessment. However, this estimated values have not been verified by sufficient experimentation [5]. Hence, it forces us to question whether these estimated values are reasonable and conservative for the engineering application [6].

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Many investigations using CFD simulation indicate that the moving body plays a significant part in indoor dynamic airflows [7–14], and a few recent studies have indicated that staff walking can greatly influence the contaminant dispersion [15]. Kalliomäki et al. [16] compared hinged and sliding doors on air exchange across doorway. Their results showed that the sliding motion induced less air exchange and passage across the doorway notably increased the airflow out of the isolation room. Villafruela et al. [7] examined the human motion's effects on airflows through a real operating room door, and determined the spatial and temporal distribution of airflow through the door by ultrasonic anemometry. Choi and Edwards [17,18] and Saarinen et al. [19] used a time-resolved Large Eddy Simulation (LES) method to simulate the human walking across the rooms, and estimated the volume of air escaping as a function of time. Hang et al. [8,12] found the potential inter-cubicle airborne transmission through a shared anteroom. As the door being opened or closed, door motion induced two-way flow across the doorway. Kalliomäki et al. [16] found that interzonal air exchange volume through doorway was influenced by door opening cycle time and temperature difference by full-scale experiments and simulations. Villafruela et al. [7] studied the effect of surgeon's different posture movement on particle distribution within the surgical area. Wu and Lin [38] conducted a series of manikin tests with different moving speeds and different moving routes. They found that movements can transport carbon dioxide under displacement ventilation.

Typically, the control room is located in the reactor auxiliary building, with many rooms surrounding it [1,2,21]. It is necessary to pass through two important rooms, the corridor and the anteroom, before reaching the core area of the CR, as shown in Fig. 1. The door between the corridor and the anteroom is the CR entrance door. When the entrance door opens, due to the air flow induced by the door and the person, inleakage occurs immediately from the corridor to the anteroom. In this study, only the first room, i.e. the anteroom of the control room, was selected to be investigated, and the core area of control room was excluded. The reason is that the door opening to the core area is normally closed. When an operator or someone seeking for shelter enters the anteroom, he will wait there for identification inspection and dose estimation, and later can be permitted to enter the core area, so the entrance door and the door to the core area would not be opened simultaneously. Since the anteroom is the first vulnerable area to the contaminant inleakage, determining the inleakage induced by a human entering through the entrance door is the subject of this paper.

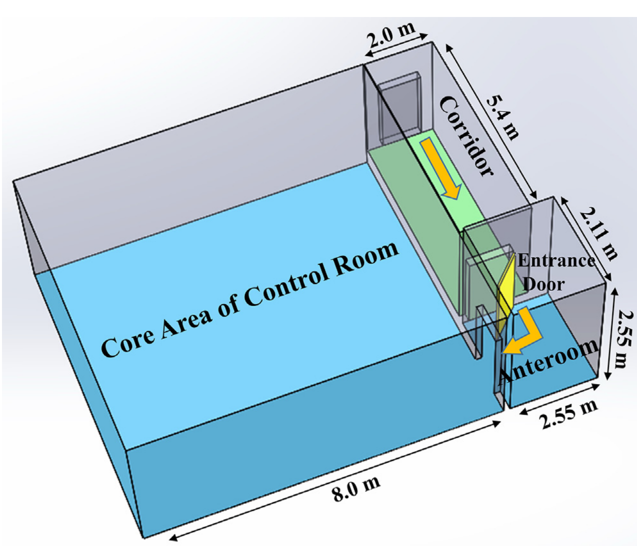

Fig. 1. The typical layout in the nuclear plant: the control room and the corridor.

In this study, inleakage airflow patterns across the control room doorway induced by the operation of single hinged with simulated human passage were examined, and the inleakage air volume was calculated. The paper addresses the following questions: how is inleakage air induced and distributed, what is the inleakage flow rate and inleakage volume, how does the entrance time affect the inleakage volume, and what is the difference between the simulation and the experiments results. The simulation studies with dynamic meshes were carried out, in which the door opens and closes and the person moves from the corridor into the anteroom. In order to monitor the dynamic inleakage air flowrate and its distribution easily, the air within the corridor was considered as contaminated air and kept a certain SF_6 concentration. Moreover, the simulation results were compared with full-scale experimental data.

2. CFD methods and setup

2.1. Control room, corridor, person

The model established for the simulation consisted of the control room anteroom and the corridor. The anteroom is the most vulnerable area for inleakage, and the corridor is the only passageway to access the control room. The anteroom is 2.55 m (L) $*$ 2.11 m (W) $*$ 2.55 m (H), and the corridor is 5.40 m (L) $\times$ 2.00 m (W) $\times$ 2.55 m (H). There is an entrance door between the anteroom and corridor, 2.00 m $*$ 1.00 m, labelled in Fig. 2. The hinged door typically used in the real nuclear plants [21] is installed with the adjustable spring door closer. It is opened by manual operation, and is closed quickly by its strong closer. A person intending to enter the control room is in an upright standing posture, just in front of the door. For simulation purposes, the person is simplified as a rectangular block. The dimensions are 0.5 m (L) $\times$ 0.2 m (W) $\times$ 1.75 m (H). In many research [8,11,22–24], the rectangular block simplification for human body was adopted to simulate the effect of the human moving wake, and after the comparison with experimental results it was found that this simplification can qualitatively predict the wake flow characteristics. Mazumdar et al. [14] used three different human geometries to study the influence of body shape on the contaminant transport, and found that the breathing level concentration with the rectangular block was only slightly higher than that with the human-like model.

2.2. Tracer gas setup

The tracer gas is widely applied to confirm contaminant dispersion. SF_6 is the most commonly used tracer gas as it is detectable at very low concentrations and distinctive from atmospheric gases [18,25].

In order to detect inleakage flow into the anteroom easily, all the air within the corridor was marked with a uniform and constant SF_6 concentration. Therefore, Eq. (1) indicates that the inleakage rate can be represented feasibly by SF_6 flowrate. When the person has entered the anteroom and closed the entrance door, the total inleakage volume can be represented by the total SF_6 amount in the anteroom, as shown in Eq. (2). When the door is opened, due to bidirectional air exchange, some air from the control room will come into the corridor, dilute the concentration near the door, and then return to the control room. In order to exclude this retracing clean air, and identify the pure inleakage corridor air, which exists initially in the corridor, we used the initial corridor SF_6 concentration c_{sc} in the equations.

$$q_{tg}/c_{sc} = q_{in} \quad (1)$$

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