NFPA (2012). In a high-rise building, stairwell pressurization systems typically utilize multiple fans distributed over the height of the stair, a ducted shaft with multiple injection points to stairwell, frequency converter for each fan and relief damper for the purpose of discharging excess air.

The system has to be designed so that the stairwells are kept clear of smoke as well as the forces on the stairwell door shall not exceed a certain value in order to occupants to be capable of opening the door to the staircase in an emergency event. The design minimum pressure difference values and maximum door handle forces are defined in various codes and standards (NFPA (2012), TUYAK (2012), BSI (2005)). During design process of pressurization system, two distinct cases are considered; all of the stair doors are closed in one case and the other case comprise of open doors (generally these doors are final exit door, door of the design fire floor, doors of the neighbors of design fire floor). The pressurization fan capacity will be much more than the required pressurization air demand in the case of “closed doors”. Maintaining acceptable pressurization can be achieved in combination of two methods, which have to be applied simultaneously; first reducing the rotation speed of the pressurization fan by frequency convertors and second implementing overpressure relief dampers to discharge the excessive amount of air.

In high rise buildings evacuation is normally phased such that occupants do not all move to the escape stairs at the same time. Instead, occupants who are most at risk (on the fire floor) evacuate first, followed by the rest of the occupants, phase by phase (Lay 2014).

For buildings, that are relatively complicated, CONTAM analysis of the pressurized stairwells is often needed to determine if the stairwell systems are capable of being balanced to perform as intended (Klote et al. 2012). The plans of high rise buildings are usually complicated; they have a basement zone (3-5 underground floors for parking lots), lobby zone, residential or office zones and utility zone having a mechanical room (Jo et al. 2007). Also they generally have a central core with vertical shafts such as elevator shafts and stairwells in their core which are surrounded by 4-7 residential units or offices on each floor.

The driving forces of air movement in buildings include naturally occurring stack effect, the wind effect and fan-powered ventilation systems. The air flow induced by stack effect is the main driver in the vertical channels and it increases with increasing temperature difference as well as the height of the building. One efficient solution for the problems caused by stack effect is to improve the overall airtightness of the whole building (Jo et al. 2007).

Stairwell compartmentation is another solution for the stack effect problems which consists of dividing a stairwell into a number of sections and each compartment has at least one supply air injection point. The main advantage of the compartmentation is that it allows acceptable pressurization of stairwells, otherwise too tall for acceptable pressurization (Klote et al. 2012). Compartmentation is not suggested for buildings where total building evacuation by the stairwell is planned in the event of a fire because the doors between compartments stay open during building evacuation thus the effect of compartmentation is lost (Klote et al. 2012).

RESEARCH METHODS

A high-rise building in Istanbul is selected as the test building for field measurements and numerical studies. The building is 156 m tall which has 38 floors above ground level and 7 basement floors. The building is a multi-use building, includes hotel and offices. Hotel rooms are located at the top of the building while the offices are placed in mid-height of the building. Ground and first floors includes ballroom, meeting room, restaurants, shops etc. Parking lots and storage rooms are located at the basement floors.

The building has two stairwells that serve all of the floors. Lobbies are provided in front of each stairwell. One of the stairwell (M1) shares the lobby with an emergency elevator. Elevator shaft can directly affect the air movement in the stair shaft, for this reason the stairwell (M2) which has its own lobby is selected. Ducted pressurization shaft is located near the stairwells and air injection in every floor is provided via louvered vent openings. M2 stairwells consist of two compartments, both stair enclosure and the pressurization shaft are divided into two at 14^{th} floor. Stairwell compartmentation wall is equipped with a door to provide transition in between the compartments. Each compartment has its own pressurization fan; the fans of the bottom and top compartment locate at 3^{rd} and 38^{th} floors respectively. The fans are identical and have a capacity of 34000 m^3/h. Relief damper of the pressurization system is located on the 38^{th} floor.

Field Measurements

Field experiments are executed in spring time. In order to reduce the effect of building occupants on experimental setup, the timing of the experiments are adjusted to be before the commissioning of the building. Two test cases are selected to obtain the effect of the compartmentation. At first field test, the door at the compartmentation wall is opened and remained open during the test to have one undivided stair shaft and the door is closed in the second field test. The climatic conditions remained almost constant for the whole duration of each test; therefore, the assumption of the steady state was done. The pressure differences across the stairwell and lobby is measured in every floor at each test.

The measured parameters in the tests include supply air velocity through the open doors, positive pressure differences in between stairwell and the building and temperatures of stairwell, inside and the outside of the building.

Pressure difference and velocity of air are measured by a differential pressure transducer (Testo 512, with a measurement range of 0 to 2 hPa) and hot wire anemometer (Testo 425, with a measurement range of 0 to 20 m/s) respectively. Both of the measuring instruments are calibrated with an inclined manometer.

Relative errors are obtained as 2.1% for the pressure transducer and 5.2% for hot wire.anemometer.

Frequency converters of the fans are set to supply constant air flow rate during all the tests. Doors of the 38th floor and ground floor and the final exit doors stayed open during the tests. It is observed that the measuring velocity with hot wire anemometer from louvered vents at 9 points is challenging, because estimating the perpendicular direction of the air flow is difficult (Hepguzel 2013). A different method is utilized to obtain air flow rate two doors stayed open during the tests; velocity at the open doors were measured with hotwire anemometer in 21 points and average velocity and air flow rate is measured. The air flow rate is multiplied with a coefficient of safety to derive the total airflow rate.

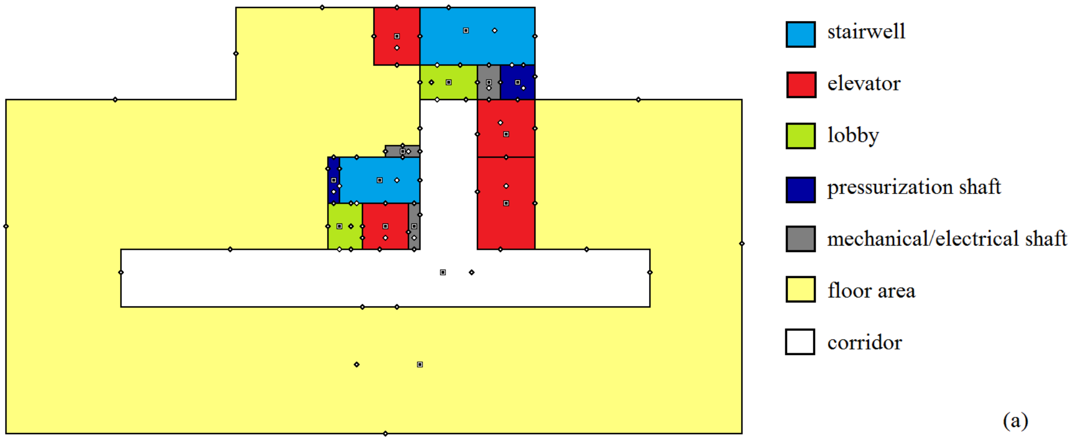
A series of tests were conducted under non-fire conditions. During the tests, the temperature values are measured in the range of 14.8°C to 15.5°C for outside air, 18°C to 21°C for the staircase and 21°C for the building compartments. Relief damper is disabled by opening the stairwell door of the 38th floor, where the damper is located.

Modeling Approach

All numerical studies were executed via CONTAM software developed by the Indoor Air Quality and Ventilation Group at the National Institute of Standards and Technologies. The software is a zonal model in which a building geometry is composed of a number of zones (rooms, shafts, floors, etc.). Each zone is treated as a lumped parameter with only hydrostatic pressure variations within the zone (dynamic pressure variations being five or more orders of magnitude smaller for the present application). Only the "long time" equilibrium pressure distributions are predicted. Details of the software can be found at CONTAM website (Anon.) and *handbook of smoke control engineering* (Klote et al. 2012).

The building model has three distinct floor plans, 38th to 15th floors serves as hotel and hotel floor plan is utilized for them (Fig.1-a), 14th to ground mezzanine floor has office floor plan(Fig.1-b), ground floor to 6th basement floor has basement floor plan. Basement floor model has same utilities as office floor model, however floor area of basement floor is seven times of the office floor area and another shaft for accessing the parking lot is created.

The height of the floors of the real building change between 2,9m to 3.5m, the height of the model building floors is 3m for every floor. M2 stairwell and its pressurization shaft run entire height of the building and openings provided at every floor from pressurization shaft to the stairwell for air supply. The essential air leakage data were obtained through literature survey and which are shown in Table 1. Lowest air leakage data is selected for walls, because hotel rooms which have openable window are empty during tests and windows of offices are not openable.



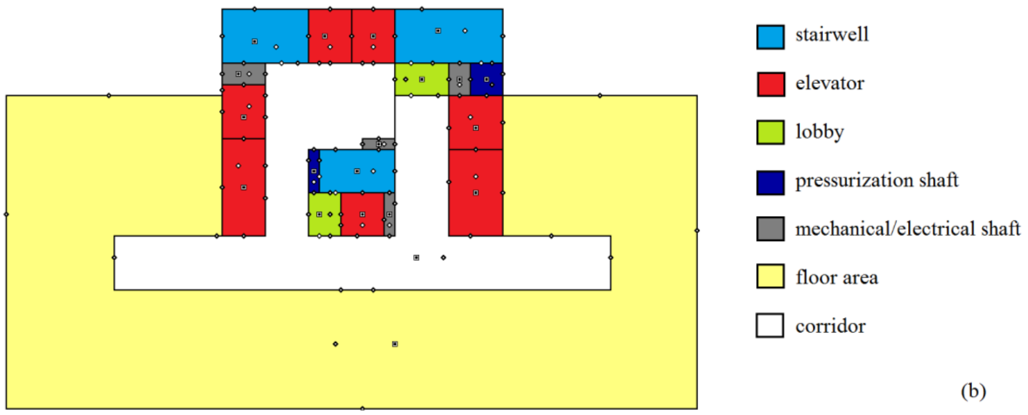


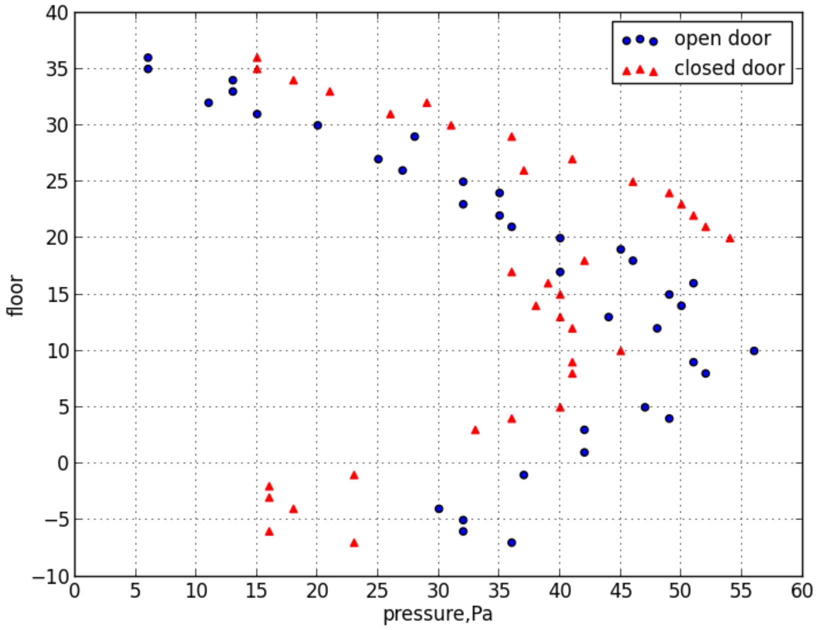
Figure 1. *Floor plans of the building model (a)hotel floors (b) office floors*

Table 1. *Air leakage data used in the model.*

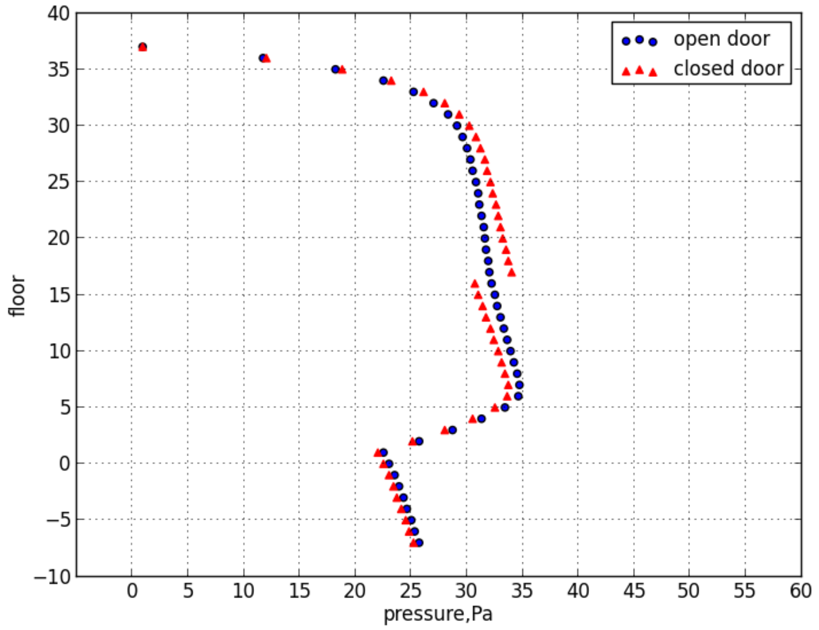
Building component	**Air leakage data**	**Source**
Exterior wall	0.5 cm^2/m^2	(Klote and Milke 2002)
Interior wall	2.0 cm^2/m^2	(Annon.A)
Stairwell wall	0.14 cm^2/m^2	(Klote and Milke 2002)
Stairwell door	73 cm^2/item	(Klote and Milke 2002)
Open stairwell door	2 m^2/item	(Klote and Milke 2002)
Typical door	70 cm^2/item	(Jo et al. 2007)
Elevator door	325 cm^2/item	(Jo et al. 2007)
Floor	206 cm^2/m^2	(Miller and Beasley 2009)

RESULTS

The major leakage of the system is the open door at 38^{th} floor, because the supply fan directly connects to supply shaft at this level. The upper floors have less differential pressure values than mid-height floors because of the above-mentioned door. Normally, under stack effect the pressure differential values of upper floors is higher.



(a)



(b)

Figure 2. *Pressure differences across stairwell door: a) field experiments b) numeric studies*

Differential pressure characteristics and order of magnitude of experiments and simulations are identical but simulation values of two-zone condition (closed-door case in Fig.2) and single-zone condition (open-door case in Fig.2) differ from the experimental values of 35% and 45% respectively. Air leakage is the most influential factor of pressure distribution. Air leakage of some components measured experimentally and used in CONTAM simulations in some studies in the literature (Jo et al. 2007) (Miller and Beasley 2009). Instead of such a study, air leakages from literature survey are used in this work.

Dividing the stairwell into two zones affects the differential pressure values to distribute in a wider range for upper floors and a narrow range for the lower floors. It is concluded both experimental and numerical studies that the air tends to flow from upper zones to lower zones in stairwell; when the stairwell is composed of two zones (closed door case in Fig.2), the differential pressure values of upper floors are increased and lower floors are decreased.

Also, differential pressure distribution expands to a narrower range in closed-door case, thus provides that the compartmantetion supports homogeneous pressure distribution in the stairwell.

DISCUSSION

Instead of only one floor plan, three floor plans is used in order to accurately model the building in this study because the building is a multi-purpose building. During modeling process, pressure distribution characteristics consistent with experimental results were obtained by using model with three different floor plans.

The most influential factor of differential pressure distribution through the stairwell is the air leakage. While creating the building model, it is observed that the use of different leakage area data change the results enormously. In order to determine the appropriate coefficient of leakage area, calibration and experimental measurements are executed in the some studies in literature (Jo et al. 2007) (Miller and Beasley 2009). Instead of such a study, leakage air data taken from literature. It is thought that modeling the air leakage needs to be developed.

The supply air flow rate was obtained by an approximation in experimental study, in which the air flow rate of the two open stairwell doors was measured and multiplied with a safety factor. Using different values of the supply air flow did not change the slope of the differential pressure versus floors, it changed only the values of differential pressure values and it caused difference in between measured values and simulation results.

CONCLUSION AND IMPLICATIONS

Compartmentation of stairwells is found in literature (Klote et al. 2012), but there is not any study in the literature which investigates compartmentation. It is concluded that compartmentation supports uniform pressure distribution on stairwells, however it has needs to prevent pressure rise in upper floors by additional mechanisms if the system is top injected.

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