THERMAL PERFORMANCE SIMULATION OF AN ATRIUM BUILDING

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ABSTRACT

In recent years highly glazed spaces and atrium buildings are seen as a sign of advanced technology. An atrium is the social center of a building where people gather for social activities and also is a significant element of passive building systems when well designed to provide user requirements.

The study aims to accomplish a thermal performance simulation of an atrium building by specifying a prototype model of an office building in Istanbul. With the help of building simulation tools - EnergyPlus (Version 1.2.3), FLUENT (Version 6.2.16)- total energy consumption and air stratification of the atrium building is performed.

INTRODUCTION

After 1970's having a common use in modern architecture, the atrium performs impressive spaces, revives the indoor space by admitting natural light, maximizes the benefit from direct solar gain, maintains solutions to the problems of natural ventilation and acclimatization, increases interaction and socialization of the people (Bryn 1993; Bednar 1986; Saxon 1986). While providing circulation and communication between stories, atrium forms comfortable buffer zones between indoor and outdoor environment. It acts as a filter of undesirable effects of outdoor environment factors such as rain, snow or wind etc., and retains the desirable effects of outdoor such as sunshine, fresh air and visual circumstances. In addition, atrium is also reported to increase the marketing values of many buildings, beside their psychological and physiological effects on increasing the moral of people and exposure to daylight (Laoudi et al 2002).

Despite these advantages of the atrium, some disadvantages cause high energy consumption like, excessive solar heat gain in summer, heat loss from largely glazing surfaces and also air stratification affect thermal comfort and performance of atrium.

Energy saving strategies of atrium can be listed as; providing natural light into occupied spaces, being a buffer zone between indoor and outdoor environment, natural ventilation with the help of stack effect. Natural lighting reduces electrical lighting and also cooling energy consumption caused by lighting equipments. Atrium's buffer zone potential decreases energy transfer from building surfaces to the outdoor environment. By stack effect, atrium and adjacent occupied zones can be ventilated naturally without any of air conditioning system.

The atrium is known to be subject to significant air stratification due to its large size and high solar gains through its fenestration, particularly in summer. Prediction of energy consumption and thermal performance of an atrium building is very difficult because of these complex thermal phenomena. Energy simulation programs developed for traditional buildings do not give accurate and realistic results in atrium buildings. Therefore estimation of air stratification and air flow patterns in atrium buildings require accurate and detailed modelling techniques (Laouadi et al 1999; 2002). Computational fluid dynamic models (CFD) require more time and powerful hardware to predict air stratification and air flow.

METHODOLOGY

This paper analyses the use of multiple building performance simulation tools for evaluating energy consumption, complex temperature stratification and air flow in an atrium building. The types of building performance simulation tools used include: EnergyPlus, Window5, COMIS and FLUENT.

Simulation Tools

In proposed simulation approach, building energy simulation program EnergyPlus and computational fluid dynamic program FLUENT were used to evaluate an accurate and realistic thermal performance of the atrium building. EnergyPlus is a new generation of building energy simulation software developed by the U.S. Department of Energy. Like other whole-building simulation programs EnergyPlus simulates building energy flows based on an input file containing a detailed description of building construction, HVAC systems and their controls. EnergyPlus calculates total (lighting, cooling and heating) energy use of office building. Direct solar heat gain through atrium glazed roof, thermal effect of transmitted sunlight on adjacent spaces can be calculated by specifying solar distribution systems. Air flow pattern can be calculated with an integrated COMIS air flow model. However, EnergyPlus does not take into account air stratification and assumes a constant mean air temperature in a zone (EnergyPlus Version 2.1.03 Help Manual 2005). Therefore, for further performance evaluation of atrium building, a general purpose commercial CFD package FLUENT was employed for the prediction of air stratification. The software employs a body-fitted coordinate system for accurate representation of a flow domain with irregular geometries such as atrium (www.fluent.com).

In addition, Window 5.2 program was used to determine thermal and optical properties of the glazing systems, which were then integrated into EnergyPlus simulation program.

Description of the Building

Three storey office building was designed for the simulation studies (Figure 1). An enclosed atrium shape which occupied a central space of the office building was selected. The atrium space was assumed for only circulation between the adjacent zones and was placed in the core of the building.

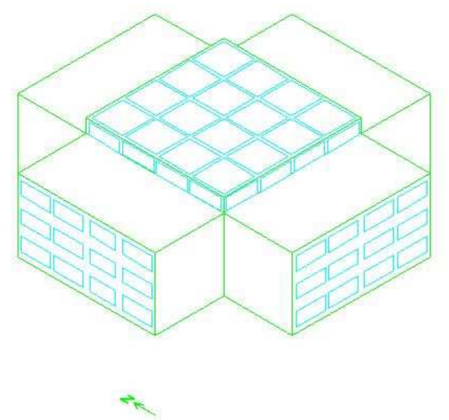


Figure 1. Perspective of the office building

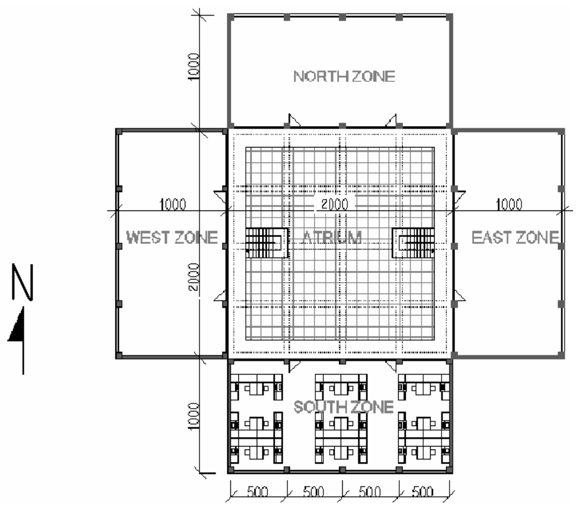


Figure 2. Plan of the office building

The physical properties of the building elements of the office building are as follows:

Thermal characteristics:

- Roof: U= 0.3 W/m^{2}K
- Ground floor: U= 0.32 W/m^{2}K
- Intermediate floor: U=4.5 W/m^{2}K (considered as adiabatic)
- Opaque part of facades (walls): U= 0.32 W/m^{2}K (without glazed part)
- Internal walls: U= 5.2 W/m^{2}K (between zones and atrium)

Other constructional properties:

- Solar radiation properties of opaque surfaces: Absorptance for solar radiation for both internal and external opaque surfaces was 0.7
- Thermal radiation properties opaque surfaces: Absorptance for thermal radiation for both internal and external opaque surfaces was 0.9

The fenestration of the office zone was placed longitudinally on the facade and 50% of the external wall area was glazed.

Two different glazing systems were used in the external and internal windows. The glazing system on the external walls was selected to reduce solar gains and heat loss; the glazing on the internal walls that separated the atrium and the office zones were designed to admit more daylight into office zones.

The atrium had a square shaped and a glazed roof. The roof glazing had the same characteristics with the glazing system on the external walls.

The frame and the dividers were made up of aluminium with thermal break and U value of the frame was 5.68 W/m^{2}K. Window 5.2 computer program was used to calculate the optical and angular values of each glazing system with the frame (Table1).

Table 1

Thermal properties of glazing systems

	U_{edge}	U_{center}	U_{total}	SHGC	VT
IG	3.192	2.611	3.012	0.75	0.74
EG	2.464	1.178	1.833	0.36	0.61
ARG	2.464	1.178	2.235	0.36	0.55

IG : Internal Glazing
EG : External Glazing
ARG : Atrium Roof Glazing
U : Heat Transmission Coefficient
SHGC : Solar Heat Gain Coefficient
VT : Visible Transmittance

Schedules

Occupancy

Since the atrium was considered as a circulation area, it was not continuously occupied. Therefore no people were modelled at the corridor or hall/staircases. There were 18 people in each occupied office zone. The office zones were totally occupied during working hours between 9.00-12.00

and 13.00-18.00 while half of the workers were assumed to be working during 8.00-9.00 and 12.00-13.00. Moreover the building was occupied only five working days in a week.

For official activities, user activity level was set as: 150 W/ person and user clothe type was considered as 1 clo in winter, 0.5 clo in summer and 0.85 clo in transient seasons (ASHRAE Standards 2001).

Heating and cooling systems

The building heating and cooling systems were on 1-h advance, in order to have reached comfort conditions beginning of the occupation period.

The heating system for the office zones was set as follows:

0.00 - 7.00 : 15° C
7.00 - 17.00 : 23° C
17.00- 24.00 : 15° C

The cooling system for the office zones was set as follows:

0.00 - 7.00 : 30° C
7.00 - 17.00 : 25° C
17.00- 24.00 : 30° C

The heating system for the atrium zone was set as follows during heating season:

0.00 - 7.00 : 10° C
7.00 - 17.00 : 15° C
17.00- 24.00 : 10° C

No cooling system was defined for the atrium zone and the atrium zone was considered to be cooled with natural ventilation.

Heat loads

The heat equipment load was specified 160 W/person assuming that each worker was using one PC. Equipments were switched on based on the same schedule of the occupancies. No other equipment was defined (Gratia et al 2003).

The electrical input to lighting ultimately appeared as the heat that contributed to zone loads or to return air.

Recessed fluorescent lighting was modeled with a lighting power density (LPD) of 0.11 W/m^2. Full LPD levels were modified by the occupancy schedule (e.g., at 8:00-9.00, 50% of full LPD was on, at 9:00-17.00, 100% of full LPD was on, at the remained hours and off days 5% of full LPD was on) in combination with daylighting controls. Heat was apportioned to the interior space (42%) as thermal radiation, (18%) as visible radiation and (40%) as convection (Lighting Handbook: Reference & Application 1993).

Daylight Strategy

Daylighting is one of the most valuable aspect of an atrium. The provision of a view, even into a semi-open space, and the ability to have natural light entering the room is important assets. Providing office lighting along the atrium perimeter is another possible beneficial daylighting role for an atrium (Gilette 1988).

In determining daylighting strategy of an atrium, the following elements act critical role; the atrium shape and section aspect ratio, the transmittance of atrium roof, the reflectiveness of the atrium surfaces and the penetration of daylight into adjacent spaces (Aizlewood 1995).

The section aspect ratio has more important influences on daylighting than the plan aspect ratio. Solar radiation can not reach the floor of the building because of high section aspect ratio (SAR) (Bednar 1986).

SAR = Atrium Height /Atrium Width

In the reference building lower section aspect ratio of 0.65 was selected.

The rationale behind the design of the office zone was to admit enough daylight. Therefore the office zone was designed as 10m deep to reduce electric lighting load. The windows on the longitudinal axis of the external and the internal walls contributed to provide enough daylight levels to reduce lighting energy use (Figure 3).

Shading effect of constructional elements of the atrium roof was taken into account. The solar heat gain coefficient (SHGC) value of the atrium roof glazing was selected as 0.36 to prevent excessive solar gain and glare problems in the atrium. Besides, high visible transmittance (VT: 0.74) glazing was selected for the internal walls, which separated the atrium and the office zones to admit more daylight into occupied zones. Because of the limitations of EnergyPlus, internal shading device was not defined for the interior windows between the atrium and the office zones. Besides the exterior windows of the office building were modeled without any shading device.

The reflectivity of the interior opaque surfaces was specified as 0.9 to distribute and project daylight into spaces.

With daylighting controls, the office zone electric lights were dimmed linearly so as to provide 500 lux at the two reference points which were located 4.50 m and 1.50 m from the external and internal window wall respectively, centered on the window and at a height of 0.76 m above the floor (Figure 3).

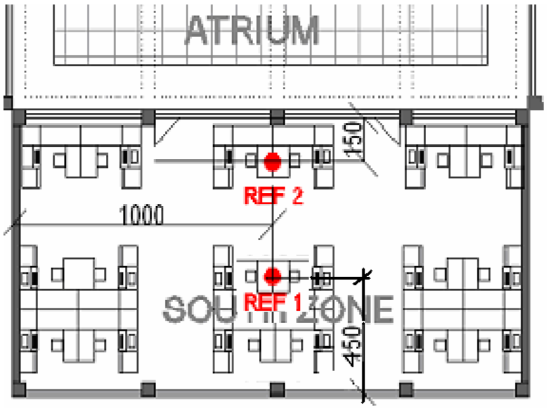


Figure 3. Reference points on office zone plan

Heating, Cooling, Ventilation (Indoor environment)

The interaction of building use and climate must be considered before selecting atrium thermal strategy. According to this interaction, atrium' thermal strategy can be listed as warm, cold and convertible types (Saxon 1986). Since Istanbul has warm temperate climate, the atrium thermal type was selected as convertible atrium which means both heating and cooling energy strategy is important to reduce yearly energy consumption of the building.

Building use defines indoor thermal condition level of atrium. According to R. Saxon, indoor thermal condition level is listed as; canopy, full comfort, buffered and tempered buffered comfort types. Indeed the main idea rely on energy strategy of atrium "buffer thinking" is first suggested by T. Farrell and R. Lebens, and these lightly constructed zone are colder in winter and hotter in summer than the fully comfort conditioned spaces (Saxon 1986).

Modern atrium applications are unfortunately rarely considered as an energy saving feature. The buildings where an atrium has been included as a part of energy strategy, the overall energy consumption of the building has been found to be lower than a comparable building on more traditional lines (Mills, 1994). When atrium is designed as fully comfort spaces, because of the excessive heat gain and loss through the glazing enclose the atrium, they cause high energy consumption.

Hereby, the use of atrium decides its thermal climate. The use and minimum temperature of the zone is documented below in Table 2: (Bryn 1995; EIA 1995)

In the study to emphasize the advantage of the buffer zone of the atrium, tempered buffered comfort type was selected. The atrium zone was tempered according to the building use.

Two natural phenomena directly affect thermal comfort and energy performance of the building that involves atrium; the greenhouse and stack effect. The greenhouse effect is created in atrium zone by the fact that short-wave heat radiation from the sun passing through glazing to warm interior surfaces (Johnson 1991).

Table 2
Building use and thermal climate

Use	minimum temperature (^{o}C)
Communication	10-14
Active Use	12-18
Relaxing, sitting	20
Plant Growing	5

In this study exterior envelope of the office building was strongly insulated in order to be protected from the outdoor environmental factors. However, the adjacent surfaces of the atrium were not insulated for providing the contribution of the atrium/office zone heating energy by the solar gain and heat loss through no insulated internal walls. Air flow between the conditioned zones and atrium were not defined in heating season because of the temperature differences between the atrium and the occupied zones. As a result atrium was heated up to 15^{o}C during occupied periods (Figure 4).

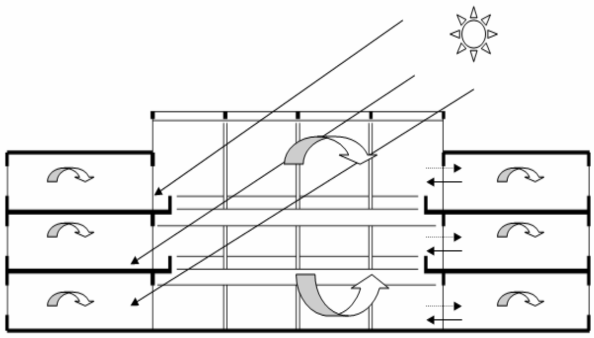


Figure 4. Atrium and office zones' energy strategy in heating season

The computing simulation using programs EnergyPlus and FLUENT, achieves to estimate the thermal performance of the atrium and the air stratification. Although EnergyPlus calculates yearly and daily energy use of the building with atrium, it does not calculate air stratification of the atrium. Therefore for evaluating the indoor temperature in each zone and the air flow rates, thermal airflow interaction was computed by using the program COMIS. Air mass flow was calculated using COMIS as in the following equation below (EnergyPlus Version 2.1.03 Help Manual 2005):

$$Q = C_Q(\Delta P)^n$$

Q = air mass flow (kg/s)
C_Q = air mass flow coefficient (kg/s-Pa)
P = pressure difference across crack (Pa)
n = air flow exponent

For COMIS calculations, it was also assumed that the atrium space was under control to be closed to the adjacent spaces The atrium space was connected with its adjacent spaces via operable windows/doors in each zone that remained closed and opened when the zone temperature was higher than the ventilation temperature and the outside temperature. In this study the ventilation temperature was set as 19ºC. Venting opening factor was set between 5-10ºC

Operable skylight windows provide air flow and reduce the stratification problem during the peak periods of high temperatures. The windows were modeled with the same venting strategy.

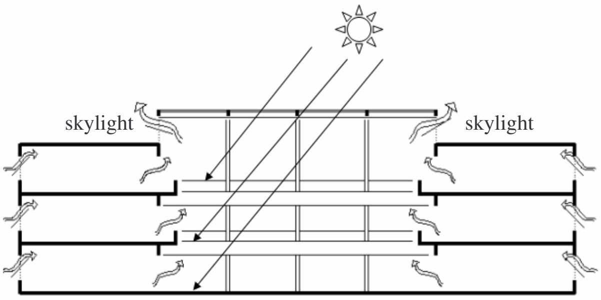


Figure 5. Atrium and office zones' venting strategy in cooling season

In cooling season, the office zone cooling system design temperature was set as 25^{o}C and the atrium was cooled with stack effect that was the result of the action of pressure differences (Figure 5).

No active HVAC system was specified in the simulations. But in order to estimate energy loads of the building, the heating and cooling set points were defined as in the given schedule in heating and cooling systems section.

Air stratification was calculated by FLUENT simulation tool with the following outputs obtained from EnergyPlus simulation program. The values which were calculated by EnergyPlus, were used as initial values of FLUENT. These were, mean air temperatures, optical and thermal characteristics of materials, convection heat transfer between real surfaces and the adjacent air. In this study, solar load model and radiation model of FLUENT simulation program were used.

Both EnergyPlus and FLUENT adjust the specified angular value - maintained from normal incidence - of transparent surfaces to the actual angle of incidence. It makes the simulation model close to real solutions.

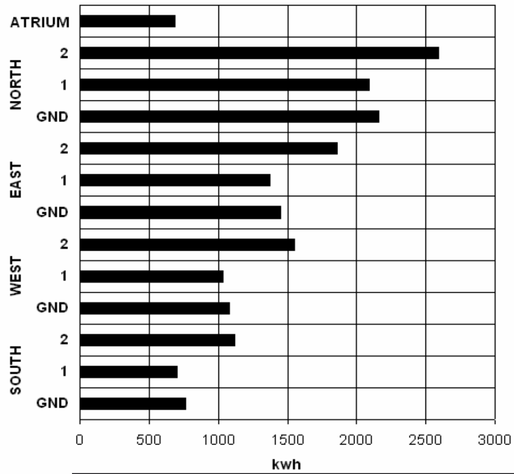
DISCUSSION AND RESULT ANALYSIS

Annual Energy Loads

The annual heating and cooling energy consumptions of the each zone are given in Figures 6-7. Heating energy consumption of the ground, first and second floors of each zone is given in Figure 6. According to simulation results, the cooling and heating energy consumptions and mean air temperatures of the intermediate floor were lower than the other floors.

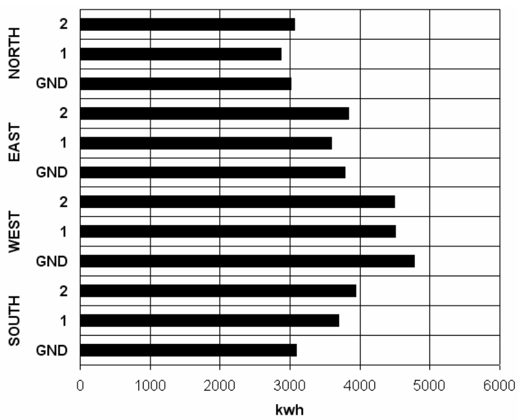
Because of the solar gain and lower heating set-point, atrium zone had the lowest heating energy consumption.

Annual cooling energy consumption is given in Figure 7. When heating and cooling loads were compared, it is seen that heating load takes the big part of energy consumption. The heating season period is longer than cooling season in Istanbul and the max outdoor temperature does not exceed 31^{o}C in summer.



	SOUTH	WEST	EAST	NORTH	ATRIUM
GND	762	1077	1447	2163	686
1	699	1037	1372	2093	
2	1122	1550	1860	2594	

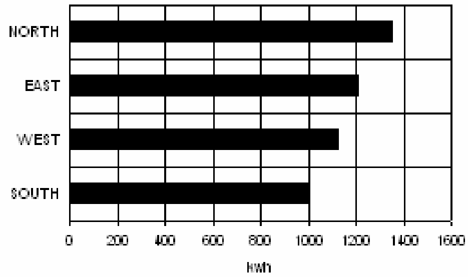
Figure 6. Annual heating energy consumption of each zone



	SOUTH	WEST	EAST	NORTH	ATRIUM
GND	3902	4776	3782	3010	0
1	3701	4505	3591	2871	
2	3945	4497	3834	3059	

Figure 7. Annual cooling energy consumption of each zone in kWh

Lighting energy loads of each zone was given in the Figure 8. Consumptions were increasing from south to north.



	SOUTH	WEST	EAST	NORTH
TOTAL	1003	1124	1209	1350

Figure 8. Annual lighting energy consumption of each zone in kWh

Thermal Performance

Mean air temperature of the office zones was calculated as 23°C, and although atrium zone's heating set-point was 15°C, solar gain impacts increased the mean air temperature during occupied hours (Figure 9). The lowest mean air temperature was calculated in North zone and East zone as 17.4°C and 17.9°C respectively. During the occupied hours, the mean air temperatures were set a constant temperature so the values were same, but during the unoccupied hours, the temperatures fluctuated from 23°C to 17°C in the zones.

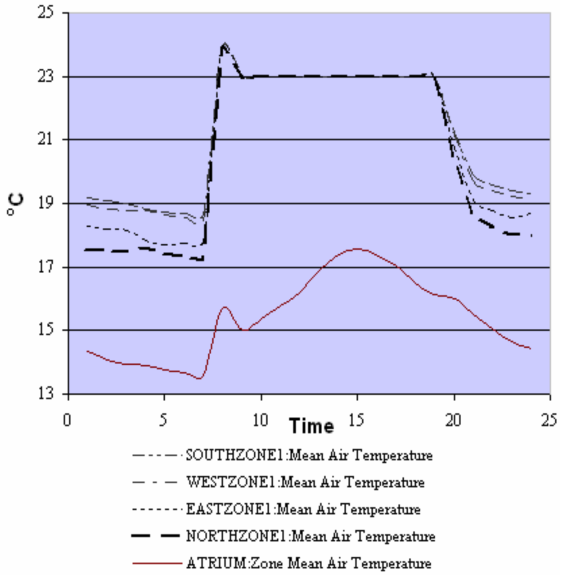


Figure 9. Daily mean air temperatures of first level of each zone and atrium (Calculated values on the21st of January)

The daily mean air temperatures calculated on the 21st of July for intermediate floor of each zone and the atrium are given in Figure 10. Although no cooling function was set, mean air temperature of the atrium zone did not exceed 30°C level.

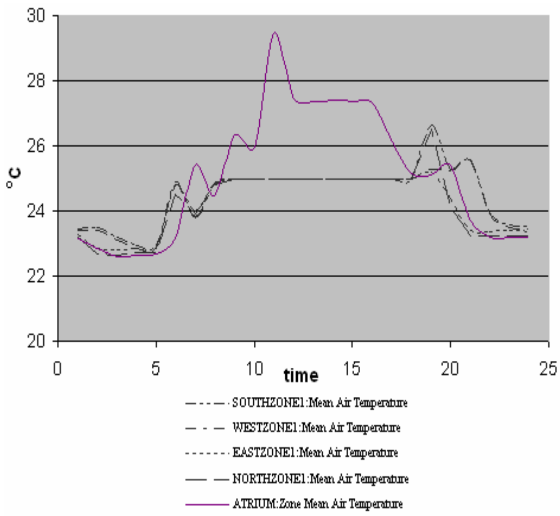


Figure 10. Daily mean air temperatures of first level of each zone and atrium (Calculated values on the21st of July)

Air flow through atrium skylights are given in Table 3. During day and night, atrium zone and office zones were cooled by the help of stack effect indirectly. Mean air temperature of the unventilated atrium reached its highest value at 16.00 as 42°C.

Table 3

Air flow values through atrium skylights on 21st July

21 July	Unventilated Atrium Mean Air Temp. [C]	Ventilated Atrium Mean Air Temp. [C]	Atrium East Skylight 1 Airflow (m3/s)	Atrium East Skylight 2 Airflow (m3/s)	Atrium North Skylight 1 Airflow (m3/s)	Atrium North Skylight 1 Airflow (m3/s)
1	31	23	17	17	26	26
2	30	23	13	13	20	20
3	30	23	13	13	20	20
4	29	23	13	13	20	20
5	29	23	13	13	20	20
6	29	23	0	0	0	0
7	29	25	0	0	0	0
8	30	24	19	19	30	30
9	32	26	0	0	0	0
10	34	26	20	20	32	32
11	37	29	0	0	0	0
12	40	27	20	20	31	31
13	42	27	13	13	36	36
14	42	27	10	10	27	27
15	42	27	11	11	28	28
16	42	27	15	15	23	23
17	41	26	0	0	43	43
18	40	25	16	16	40	40
19	38	25	22	22	34	34
20	36	25	13	13	36	36
21	35	24	15	15	24	24
22	33	23	16	16	25	25
23	32	23	13	13	20	20
24	32	23	14	14	21	21

Air Stratification

The air stratification problem was solved excluding the radiation effects, and then radiation model was included in the calculation to evaluate the effect of radiant heat exchange between the internal surfaces. For all opaque and transparent materials the absorptivity for the infrared and visible bands were recorded.

The air temperature distribution which is the output report of FLUENT is given in Figure 11. The values were calculated on the 21st of January at 15.00 pm.

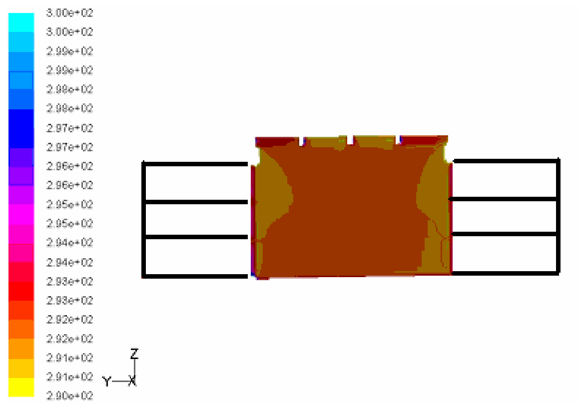


Figure 11. Air temperature distribution of unventilated atrium (Section through south and north axis of building) (Calculated values on the21st of January at 15.00)

In order to calculate air stratification of atrium by the help of FLUENT, boundary conditions of materials (such as inside surface temperature, thermal conductivity, heat flux) and air (air temperature) were set in accordance with the output data of EnergyPlus.

As mentioned before, because of the solar gain and airflow interaction, a uniform air temperature distribution does not perform in atrium volume. Although the unventilated atrium mean air temperature was reported as 17.8^{o}C (Figure 9) on 21^{st} of January at 15^{00} and 42^{o}C (Table 3) on 21^{st} of July at 15^{00}, the differences in distribution of air temperature were seen in Figure 11 and 12.

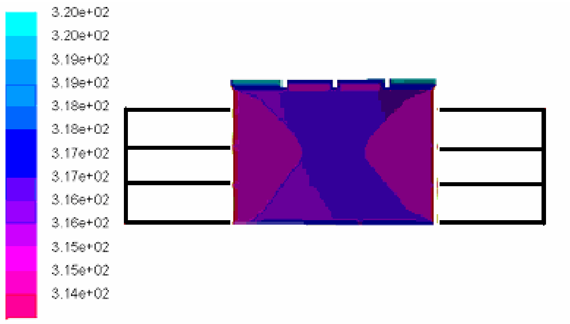


Figure 12. Air temperature distribution of unventilated atrium
(Section through south and north axis of building)
(Calculated values on the21^{st} of July at 15.00)

Consequently, the result of calculations with the use of EnergyPlus output data shows the characteristic phenomena of air stratification in atrium.

CONCLUSION

This study comprised a simulation approach to estimate the thermal performance of the atrium by specifying a prototype model of an office building with atrium space in Istanbul. For evaluating the thermal performance of the office buildings with atrium total energy consumption (heating, cooling and lighting energy use) was calculated with EnergyPlus (version 1.2.3), and the air stratification in atrium was simulated with CFD program FLUENT (version 6.2.16).

The energy strategy of the building has been given in two stages; daylighting, heating, cooling and ventilation.

A series of comments that summarize the most significant outcomes of this work are:

- Heating energy consumption was higher than cooling energy consumption. To reduce cooling energy consumption solar control strategy could be driven, but because of the limitation of EnergyPlus internal shading devices were not defined for the interior windows of the office zones facing the atrium space.
- Lighting energy consumption does not reach high values, because of the daylighting strategy of the building.
- Thermal performance of the atrium building was shown on the two characteristics days of Istanbul. The daily mean air temperatures of atrium calculated on the 21^{st} of January showed the greenhouse effect on the thermal performance of the atrium. The highest temperature calculated in the atrium zone was 18^{o}C in winter. The daily mean air temperatures of atrium calculated on the 21^{st} of July confirmed the expected cooling impact of the stack effect.
- By using FLUENT, air stratification of unventilated atrium in winter and summer periods was evaluated. Initial values were taken from EnergyPlus, and modifications were achieved to obtain a realistic thermal and energy performance of atrium.

It is shown that atrium must be designed as a part of energy strategy of the building. Designers should be conscious of building use and thermal climate of an atrium. Amenities of full comfort conditioned atrium always attract users' interest. From the view point of energy saving, full comfort conditioned atrium attribute energy load of the buildings.

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