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CFD Based Numerical Study of Pilgrim's Movement around Kaab'a

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Abstract:

Tawaf is one of the most important rituals of Hajj/Umrah pilgrimage and is performed in the Mataf area of the holy mosque 'Al-Masjid Al-haram' in Mekkah. During Tawaf each pilgrim walks counter clockwise, seven times in circular movements around Kaab'a, which is situated in the Mataf area. Every year thousands of people go for Hajj and Umrah from all over the world and face difficulties during Tawaf around Kaab'a, particularly in rush hours, specially old men, women and children. The purpose of this research works is to analyse the pilgrim's movement around Kaab'a during Tawaf in different scenarios and highlights the reasons that causes the difficulties in pilgrim's movement during Tawaf. 2D computational fluid dynamics (CFD) based, time dependant discrete phase langrangian particle dynamics approach is used to study the pilgrim's movement around Kaab'a in this regard. These analyses highlighted the main reasons that cause the difficulties in pilgrim's movement during Tawaf. In long run the goal is to suggest some optimize ways to reduce the turbulence (crowed density) caused by the pilgrim's movement during Tawaf.

Keywords: *Tawaf; CFD; Mekkah; Pilgrimage*.

1. Introduction

Tawaf is one of most important rituals, when Muslims perform Hajj and Umrah in the holy city of Mekkah. Tawaf is the process of circumambulating the Kaab'a seven times in the counter clockwise direction. Movement of pilgrims in rush hours especially during hajj and Ramadan season causes crowed congestion, which cause pilgrims to move in from various directions at the same time [1]. The important factors that have major contributions to the crowed of the Mataf are[2];

- The effect of the geometry (*the physical structure*) on the crowd.
- Attraction points including Hajar Aswad, Multazam, Maqam Ibrahim, Hijir Ismail and the area surrounding Kaab'a as well as relevant activities such as crossing to these attraction points.

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- The ritual activities such as queuing for Hajar Aswad, making "*Supplication* " at Multazam, praying behind Maqam Ibrahim, carrying of "Jenazah", joining and leaving the area, causing excessive crossing
- Hurdling behavior of some people such as clustering and the chain-like behavior.

Figure (1) shows Aerial View of Tawaf in Mataf Area. This aerial view has been taken at rush hours when the Mataf is completely occupied by pilgrims.

Tawaf has several properties that have major contribution to the crowed, which make simulating it particularly challenging [3]; ***a)Heterogeneous population***; at any given moment, different pilgrims may move with different purposes, ***b) High density***; the crowd density throughout the Mataf often varies considerably, and ***c) Varying velocities***; the velocity of the pilgrims in Mataf can vary depending on their location in the Mataf.

Figure 1: Aerial View of Tawaf in Mataf Area of 'Al-Masjid Al-haram' in Mekkah.

Global Positioning Systems (GPS) and Geographic Information Systems (GIS) has been used to identify the most crowded zones and to analyse pedestrian movement while performing Tawaf [4]. The congested zones have been obtained by evaluating the pedestrian average speed at different zones in the Mataf. Mataf was divided into seven zones and then average speed of pedestrian was evaluated in each zone. Results showed that zones six and seven have the slowest average speed and are most crowded as compared to other zones (Figure-2). Zones 6 and 7 are most crowded due to several factors, such as; devotional rites, pilgrim's behaviour while they circumambulating the Kaab'a and the existing Mataf design. The crowed congestion in these zones is observed constantly during hajj and Ramadan seasons.

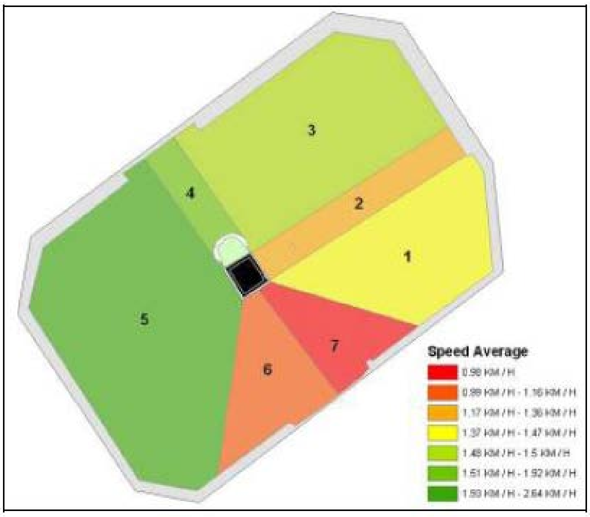


Figure 2: Color-coded map showing the pedestrian average speed at different zones, [4]

The authors in [5] studied the effect of location of the Mataf gates from the beginning line of performing Tawaf and flow pattern at the gates on the duration of pilgrims circumambulate the Kaab'a. They suggested building columns to avoid bi-directional flow at the Mataf gates. Also as per them, using proper gates to enter the Mataf will help to avoid opposite flow directions inside the Mataf [5]. To alleviate the problems associated to circumambulation of the Kaaba'a, different researchers proposed various solutions. The ideas of these proposals were mostly based on the computer simulations models or based on the direct measurements and observations. Some of these proposals are as followed:

- **Spiral Path Design**

A design was proposed by Haboubi [6], which suggested building a spiral path around the Kaab'a, which encircles it seven folds where the entrance of the path is at the outermost fold and the completion of the Tawaf is at the innermost fold leading down a ramp to an underground tunnel. One of the advantages of the spiral path design was that the pilgrims do not need to count the number of times, as they circumambulat the Kaab'a. However, the construction of the underground tunnel was considered to be unrealistic as the area of Tawaf is historical and building an underground tunnel may disrupt the area. Due to historical exclusiveness of the Mataf suggested alternatively building an overhead bridge that can link the centre of the Mataf to the exit of the mosque [5].

- **Undirected situation**

To control the circumambulation of the pilgirams around Kaab'a waiting areas at different locations in Mataf area were suggested [5]. This design approach requires plotting of many waiting points that needs to be plotted carefully so that the pedestrians would move in the correct direction and in a circular motion.

- **Removing beginning line of Tawaf**

The authors in [4] suggested some obstacles in Mataf area need to be removed to facilitate pedestrian movement in the Mataf and on the roof. One of such obstacles is the beginning line of the Tawaf which delays pedestrian movement. This suggestion has been implemented and was also simulated [3]. Observations showed a significant increase in the average velocity of the pedestrian at the most crowded zone of the Mataf.

- **Adding foldable platformin Mataf**

The authors in [7] proposed a mechanical solution model (foldable platform), able to increase the capacity of Tawaf area in a systematic way without disturbing the current design of the Mataf. The platform provide enough space for 1183 wheelchair in the first floor or 2461 person, and when the platform is not needed it can be unfolded. This proposal has been accepted and implemented by Saudi Government this year and is expected to be in service during the month of Ramadan. The mechanical platform is used as temporary solution to increase the Mataf capacity since the Saudi Government has launched a big project to increase the Mataf capacity. The new project caused to disable some areas that are used for Tawaf temporary so the mechanical platform will provide extra area for Tawaf until the project is completed.

- **Gates as entrances and others as only exits**

The authors in [5] simulated the pilgrim movement in Mataf area and suggested restricting gates as entrances and others as only exits. Also he found that building columns at exits guide, the pilgrims from both sides to walk in their own paths, which can minimize the interaction between the paths of pilgrims from two different exits and will allow pilgrims to complete their Tawaf smoothly.

- **Opening of the Al-Hateem area to Tawaf**

A circular cellular automata model was used by The authors in [2] to simulate the Tawaf movement. The software was used to predict whether changes to the area or to the operation of the place would create a significant gain in the throughput of the system. The results have shown that opening of the Al-Hateem area to Tawaf, would provide 1580 pedestrians or 17% more throughput in a 2-hour periods. This proposal cannot be implemented in reality due to religious and they proposed it for analytical purpose.

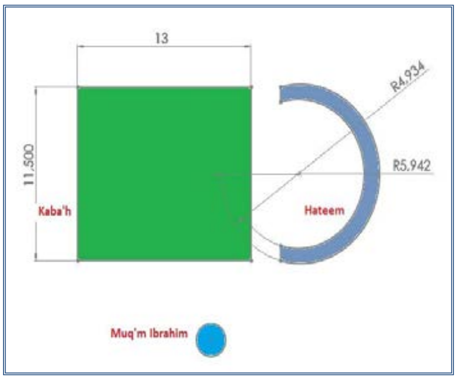
Various simulation models and software packages are available to simulate the movement of pedestrians either during evacuation or normal movements. The unrealistic or limitation in the accuracy of the simulation results are mainly due to; 1) limitation to simulate relatively small crowds, 2) limitation in simulating the dynamics interactions between pedestrians during the Tawaf, and 3) limitation in simulating the heterogeneous pedestrians' flow; as males, females, young, children, and old people perform Tawaf at the same time. Due to such complex pedestrians' flow in the Mataf particularly during the last tenth of Ramdan and hajj season; producing a more accurate simulation remains challenging problem. Various methods of modelling crowd movements have been used and reported in the literature; Physics-based models like particle and fluid dynamics model, force-based methods, matrix-based models and rule-based models are among the most commonly used methods .

Crowd simulation software's can be categorized into two groups, evacuation and normal situation [8]. *Evacuation simulation software* is used to calculate the amount of time it takes for all pedestrians to exit a building or an area under emergency conditions. *Crowd simulation software* for normal situations is used to simulate crowd movements in a normal or non-emergency situation. Zarita [5] used Microscopic Pedestrian Simulation Model (MPSM) to determine the pedestrian's movement, where pedestrians are treated individually. Ossy [9] used a technique of steering behaviour to develop macroscopic simulation crowd of Tawaf ritual. *Steering is the ability to navigate around their world in a lifelike and improvisational manner. Ossy et al.* evaluated the steering technique on several pilgrims' general behaviours, i.e. walking to certain direction, collision avoidance, and obstacle avoidance behaviour and concluded that steering behaviour of the path flocking is a better model for Tawaf crowd simulation than the path following or flocking method alone. The authors in [10] simulated the pilgrims movement using EmSim model and did a quantitative study to examine the effect of different structural design solutions in an enclosed area on crowed management and safety. The simulation and quantitative study showed that the adjustments of small structural features in an enclosed area can have large potential effects in terms of crowd safety and crowed management. Structural design issues of Mataf area are one of the important reasons of crowed turbulence that occur in the Mataf area. This does not mean that other reasons, reported in the literature are not considerable. However if the structural design of the Mataf is optimized the other reasons that cause crowed and turbulence in the Mataf can decay dramatically.

2. Numerical Setup

Simulating the pedestrian's flow in the Mataf area, using computational fluid dynamics (CFD) can be a good way to help the researchers to better study the insight reasons of turbulence that may occur in different locations of the Mataf area. CFD will not simulate the behaviour of every individual agent in the Mataf rather than, it will simulate the behaviour of the whole pedestrian's flow. In this study we have considered important design aspects and pedestrians behaviours during the Tawaf to understand the ability of CFD tools to study the problems related to the Mataf. During this research work, 2D computational fluid dynamics based time dependant discrete phase, langrangian particle dynamics numerical approach was used to simulate the pilgrim's movement around Kaab'a. The area around kaab'a was divided into three zones, where the pilgrims have different velocity in each zone. Incompressible discrete phase CFD modelling approach was used, where each pilgrim was represented by a spherical solid particle. These solid particles were released from inlets of each zone specified around Kaab'a. Interaction of each solid particle with other particles was also assumed to predict the turbulence and pilgrim's concentration more realistically and accurately. The simulations were performed, fort=10 min with Δt=0.2 sec. Geometric dimensions (in meters) of Kaab'a model used for CFD simulations is shown in Figure (3)

The Mataf area is divided into three zones since the pedestrian's density around Kaab'a (*number of pedestrians per square meter*) takes different orders and their movement velocity change accordingly. It was observed that in the zones which are very close to Kaab'a, where the pedestrian's density gets very high the pedestrian's velocity decrease significantly. As the pedestrians get further from the Kaab'a while they are performing Tawaf, their density decrease and movement velocity increase. Such division of Mataf area helped in simulating the real time observations. Figure (4) shows snapshots for pedestrian's movements around Kaab'a at different densities. It is obvious from the snapshots the pedestrians are able to move freely at their desire velocity as they move from Kaab'a towards outer zones of Mataf and when the density inside Mataf gets low. However, at high densities scenarios during rush hours the pedestrian's cannot select their path and velocity. The generated pressure - ıp of pedestrians pushes them to move towards the low pressure zones.



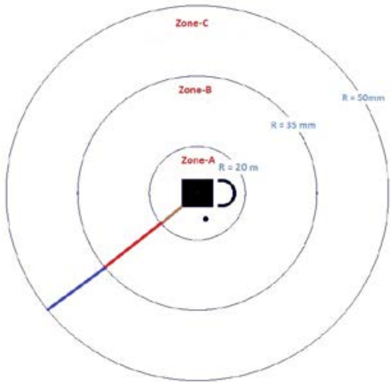


Figure 3: Geometric dimensions *(in meters)* of Kaab'a model used for CFD simulations.

Figure 4: Shows snapshots of pilgrims during Tawaf around Kaab'a

3. Results & Discussion

To simulate the pilgrim's movement around Kaab'a, three different case scenarios were analysed during this CFD based numerical study. Following are the three cases in this regard:

- Pilgrims movement around Kaab'a in 50 m circular radius
- Pilgrims movement around Kaab'a in 50 m circular radius considering the groups of people.
- Pilgrims movement around Kaab'a considering full scale model with groups of people.

3.1 Pilgrims movement around Kaab'a in 50m circular radius

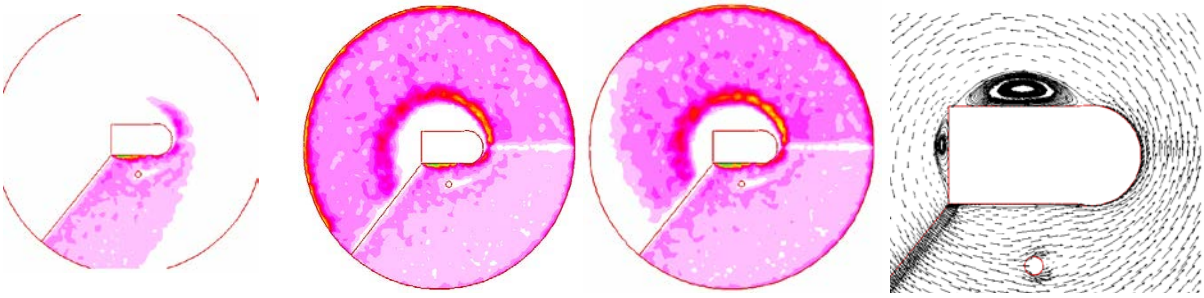
In this first case, we have simulated the pilgrim's movement in a circular radius of 50 m around Kaab'a at constant average speed of 0.7 m/sec of pilgrim's in all three zones. In this study, a simple circular model was used just to understand the pilgrim's movement in Mataf area. Two sub cases were analysed in this study, where in first case it was assumed that pilgrims are moving without crossing each other, whereas in 2nd case crossing of pilgrims during Tawaf is also included. Table-1 shows the operating conditions used for each sub case study, where angle normal to surface means that the pilgrims are moving in their normal direction, based upon their location round Kaab'a. Here we consider no crossing from one zone to another. Angular movement normal to the surface means that pilgrims are crossing each other from one zone to another'.

Analyses of case-1 (Figure-5) show a considerable change in the pilgrim's movement in case of crossing in comparison with no crossing. A low concentration of pilgrims is observed around Kaab'a, when pilgrims move in their normal direction of movement without any crossing, which leads to low turbulence near Kaab'a, but in case of crossing from one zone to another a high pilgrim's concentration area is observed particularly around Kaaba'a and also at locations of crossing, which leads to potentially high turbulence possibilities. Pilgrims from outer zones of Tawaf around Kaab'a try to move in the inner zones near Kaab'a and causes restriction in other pilgrim's movement that raises the level of turbulence and leads to problems for other pilgrims.

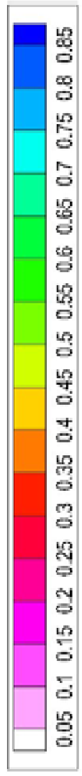
Table 1: Simulated cases for pilgrim's movement in 50 m circular radius

	Velocity (m/sec)	Angle (degree) Normal to surface
Case 1A		
Zone-A	0.7	0
Zone-B	0.7	0
Zone-C	0.7	0
Case -1B		
Zone-A	0.7	0
Zone-B	0.7	1.145
Zone-C	0.7	1.7178

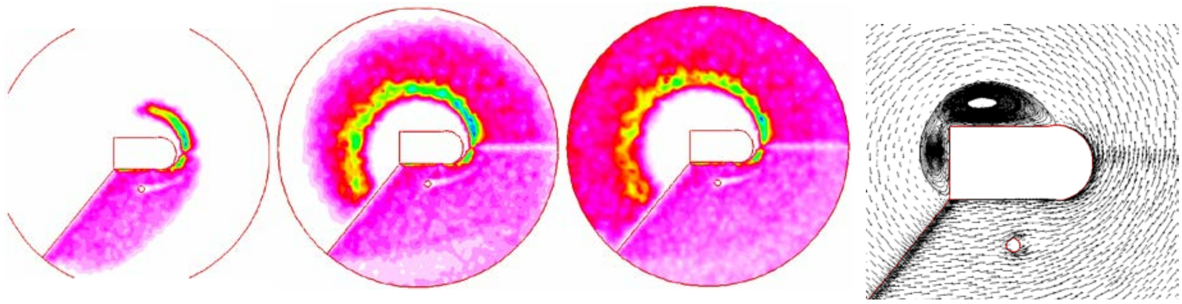
Case– 1A (no crossing of pilgrims):



(t=1min) (t=5min) (t=10min) (Velocity vector)



Case– 1B (crossing of pilgrims):



(t=1min) (t=5min) (t=10min) (Velocity vector)

Figure 5: Pilgrim’s concentration for situations of crossing and no crossing; case 1.

3.2 – Pilgrims movement for 50m circular radius with groups of people

Many people move in groups around Kaab’a and they made as sort of boundary around their group members, when they move. This causes the blockage for other pilgrims and raises a level of possible level of turbulence. In this section, a study has been carried out to analyse the pilgrim’s movement, when they move in groups around Kaab’a. In these simulations, these groups are assumed as hurdles for other pilgrims. These simulations were carried out again for a pilgrim’s constant average velocity of 0.7 m/sec assuming crossing and no crossing of pilgrims in Mataf area. The characteristics data used for simulation of case 2 is summarised in Table 2.

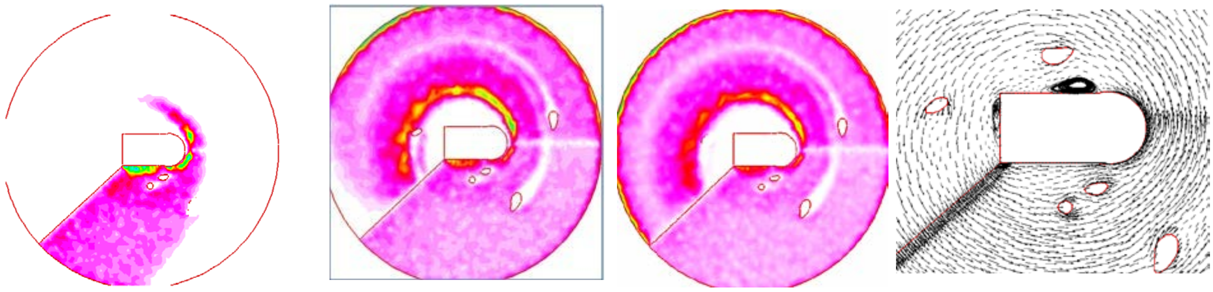
Figure (6) shows a snapshot of pilgrims performing Tawaf in shape of group. Simulation of case-2 is Figure (7)

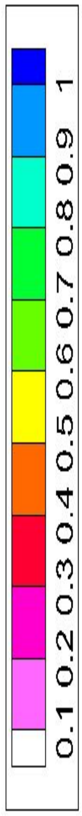
Figure (6) shows group of pilgrims performing Tawaf as group move together.

Table 2: Simulated cases for pilgrim's movement in 50 m circular radius, assuming group of people

	Velocity (m/sec)	**Angle (degree) Normal to surface**
Case– 2A		
Zone-A	0.7	0
Zone-B	0.7	0
Zone-C	0.7	0
Case-2B		
Zone-A	0.7	0
Zone-B	0.7	1.145
Zone-C	0.7	1.7178

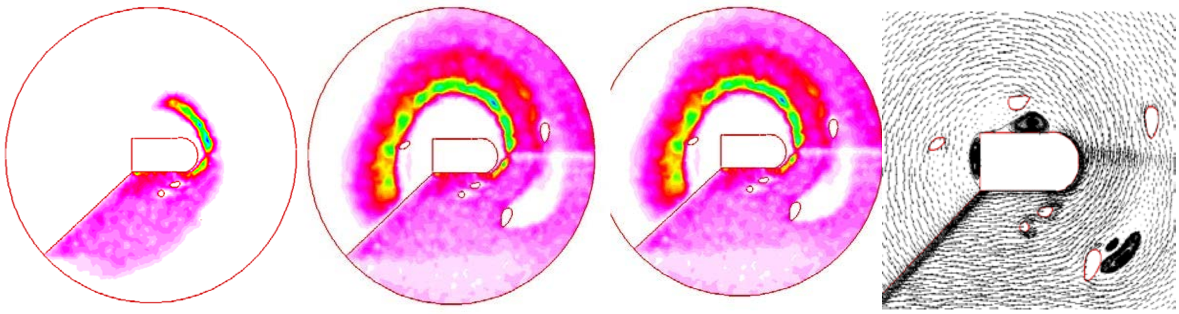
Case– 2A (no crossing of pilgrims)





(t=1min) (t=5min) (t=10min) (Velocity vector)

Case– 2B (Crossing of pilgrims)



(t=1min) (t=5min) (t=10min) (Velocity vector)

Figure 7: Pilgrim's concentration for situations of crossing and no crossing; case 2.

Analyses show a considerable change in the pilgrim's concentration and resultant turbulence level when groups of people are considered in the Tawaf zone. These groups restrict the movement of other pilgrims and cause an increase in the turbulence level during Tawaf.

3.3 Full Scale Model of Kaab'a

After the initial study of pilgrim's movement around Kaab'a in circular zones (case 1 & 2), a detailed full-scale numerical study of Pilgrim's movement is carried out assuming the actual geometric dimensions of Mataf area (Figure-8). Initial studies provided us a base for understanding the pilgrim's movement in different scenarios. This full scale study was carried out considering the small groups of pilgrims in Tawaf zones and assuming that pilgrims are crossing each other from outer zone to inner zones with an average pilgrim's speed of 0.7 m/sec. Simulation of these cases at different intervals is shown in Figure (9)

It is evident from geometric dimensions of Mataf area that it's not equally distributed around Kaab'a. As on horizontal axis, one end is 46 m wide, where as other end is 37 m wide. Similarly on vertical axis, one end is 64 m wide, where as other end is 82 m wide. This unequal geometric distribution can leads to a turbulent behaviour of pilgrim's movement.

Full scale analyses show that when pilgrims move from wider part of Tawaf zone to the narrow path, this leads to more pressure on pilgrims movement in narrow zone like from wider part of 82 m to narrow path of 37m, while velocity vector and streamlines around full scale 2D model of Mataf area, at, t= 10 min is shown in Figure (10).

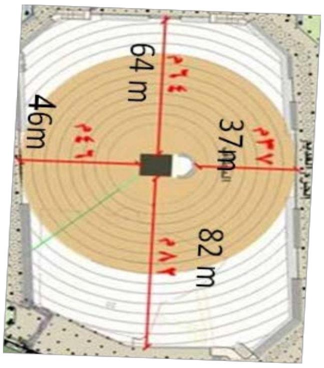
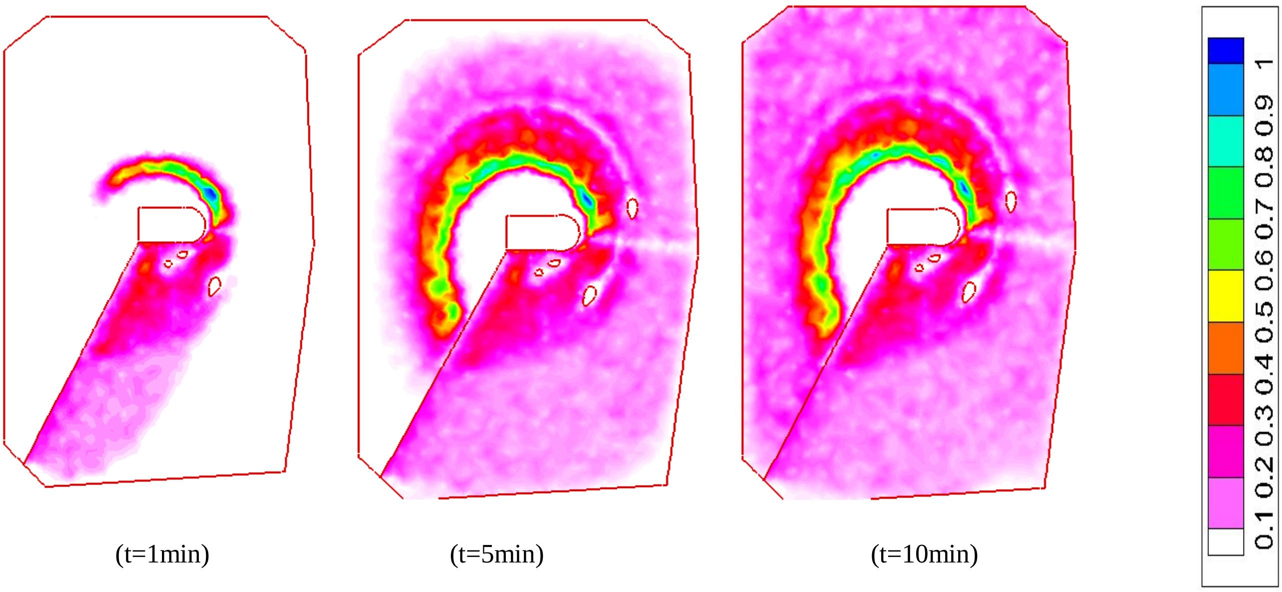


Figure 8: actual geometric dimensions of Mataf area



(t=1min) (t=5min) (t=10min)

Figure 9: Pilgrim's concentration for situations of pilgrims crossing.

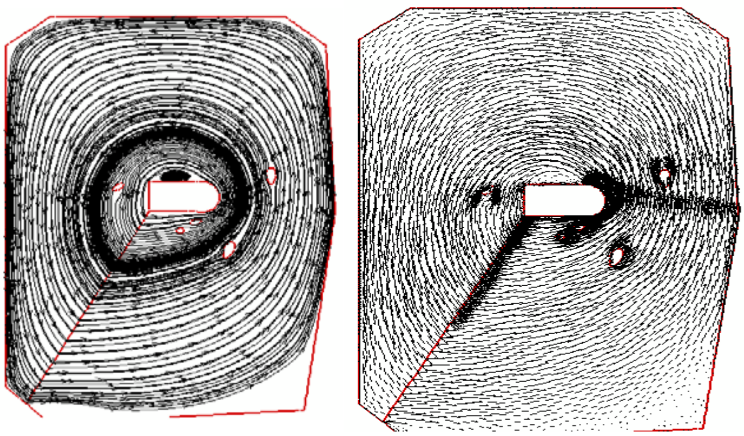


Figure **10**: Velocity vector and streamlines around full scale 2D model of Mataf area, at, t= 10 min

4. Conclusion

Computational fluid dynamics based numerical simulation is a useful way to simulate the movement of pedestrians in dense and crowded areas and when the pedestrian movement is restricted to a particular direction such as in Mataf. Following are some initial findings of this preliminary research work:

1) Low turbulence is observed, when pilgrims move in their respective circles and do not cross over from outer circular zones to the inner one.
2) High turbulence is observed in case of crossover of the pilgrims. As pilgrims from outer zones try to come closer to the Kaab'a it leads to a cross over and restricts the movement of other pilgrims.
3) High turbulence areas are observed near the Muqam Ibrahem and also towards other end of the Kaab'a and Hateem area. And strength of this turbulence increases with the increase of cross flow movement from outer to inner zones. This result is similar to fluid flow around a stationary obstacle such as circular cylinder placed in a uniform flow.
4) The movement of pilgrims in groups causes the restrictions in movement for other pilgrims. This acts as boundary wall for others. This causes the increase in turbulence and restriction in movement of other pilgrims. This result is similar to fluid flow around a dynamic obstacle such as circular cylinder placed in a uniform flow.
5) Full scale analyses show that when pilgrims move from wider part of Tawaf zone to the narrow path , this leads to more pressure on pilgrims movement in narrow zone like from wider part of 82 m to narrow path of 37 m. This result is similar to fluid flow through a bottleneck.
6) More pilgrims try to stay near the Kaab'a wall or Maqam Ibrahem for prayer, which also causes as restriction in movement of others and leads to an increase in the turbulence. This result is similar to fluid flow over a rough surface.

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