THE HEATING SYSTEM
OF
TURKISH BATH

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ABSTRACT

THE HEATING SYSTEM OF TURKISH BATH

The beginning of bathing action lies in the prehistoric times and the bathing had an important role in the daily life in the Hellenistic period for the first time. Romans, who had been influenced by the bath techniques in the Hellenistic period, improved architecture and heating system technologies of the baths and made them an important part of their life. The Roman bath culture that spread in Anatolia was turned by the influence of Turks into the Turkish bath and still goes on today. Because of the fact that, investigations are not enough about heating system of Turkish bath, to the best of the author' knowledge, thermal analysis' studies have not been done, the plan and projects of the heating systems of the bath and thermal conditions of the bath have not been investigated; extensive researches become necessary. On the other hand, energy efficient solutions with consideration of the environmental impact should be developed for historic bath buildings which are allowed for a restoration process.

The study has been concentrated on the documentation of the information about the heating systems of a Turkish bath, therefore the Alibey bath from the Ottoman period; is chosen to investigate the use of heating systems from past to present. The study focuses on the evaluation of the collected information about the Alibey bath in order to examine the relationship between traditional heating systems and under floor heating systems of the Alibey bath. In the study, thermal analysis of the Alibey bath and the energy efficiency of two different systems are determined for different operating conditions by using the ANSYS Fluent commercial code. In addition to this, field surveys are composed of freehand sketches for architectural details, temperature distributions and flow analyses of different sections of the structure are examined.

As a result of this study, two heating systems, old and new, are compared thermally. In the heating system with hypocaust, the amount of fuel to be consumed is relatively higher than the floor heating system. Besides, the temperature distribution in the floor heating system is more homogeneous than the hypocaust system.

ÖZET

TÜRK HAMAMLARINDA ISITMA SİSTEMLERİ

Tarih öncesi devirlere kadar dayanan yıkanma eylemi ilk kez Helenistik dönem günlük yaşamında önemli bir yere sahip olmuştur. Helenistik dönemde yapılan hamamlardan etkilenen Romalılar, hamamların mimari ve ısıtma sistemi teknolojilerini geliştirerek yaşantılarının önemli bir parçası haline getirmiştir. Anadolu'da yayılan Roma hamam kültürü, Türklerin de etkisiyle Türk hamam kültürü olarak gelişmiştir ve hala günümüzde devam etmektedir. Günümüzde hala Türk hamamlarının kullanılıyor olması ve özelikle bazı bölgelerde günlük yaşamın önemli bir ritüeli olmasından yola çıkarak hamamların ısıtma sistemiyle ilgili, yazarın bilgisi dâhilinde, yeterli çalışma olmaması, hamamlarla ilgili ısıl analiz çalışmalarının yapılmamış olması, hamamların ısıtma sistemlerine ait plan ve projelerinin ve ısıl şartlarının yeterince araştırılmamasından yola çıkarak kapsamlı araştırmalar yapmak gerekmektedir. Diğer taraftan, restorasyonu söz konusu olan tarihi hamam yapılarında enerji verimli çözümlerin, çevresel etkinin de göz önüne alınarak geliştirilmesi gerekmektedir.

Bu çalışma kapsamında, Osmanlı dönemi yapısı olan ve hala aktif olarak kullanılan İzmir Alibey Hamamı'nın geçmişte ve şuanda kullanılan ısıtma sistemi incelenmiştir. Çalışmalar, bu yapıların geçmişte kullanılan geleneksel ısıtma sistemi ve günümüzde kullanılan yerden ısıtma sistemi hakkında toplanılan bilgilerin karşılaştırmalı değerlendirilmesi üzerine yoğunlaşmıştır. Bu çalışmada, ANSYS Fluent ticari kodunun kullanılmasıyla farklı çalışma koşulları için Alibey Hamamının ısıl analizi gerçekleştirilmiş ve iki farklı sistemin enerji etkinliği belirlenmiştir. Bunlarla beraber yapıya ilişkin serbest yazım ve çizili anlatım, yapının farklı kesitlerinin sıcaklık dağılımları ve akış analizleri gerçekleştirilmiştir.

Bu çalışmanın sonucunda eski ve yeni iki ısıtma sistemi arasında karşılaştırmalı bir ısıl analiz gerçekleştirilmiştir. Hamamın hypocaust sistemi kullanılarak ısıtılması durumunda harcanacak yakıt miktarının yerden ısıtma sistemine göre daha fazla olduğu görülmüştür. Bunun yanı sıra, yerden ısıtma sisteminde sıcaklık dağılımının, hypocaust sistemine göre daha homojen olduğu gösterilmiştir.

TABLE OF CONTENTS

LIST OF FIGURES vii

LIST OF TABLES.. x

CHAPTER 1. INTRODUCTION 1

1.1. Argument 1

1.2. Procedure 5

CHAPTER 2. LITERATURE SURVEY.. 6

2.1. Roman Bath 6

2.1.1. Architectural Characteristics in Roman Bath 7

2.1.2. Heating System in Roman Bath 8

2.2. Historical Turkish Bath in the Ottoman Period 9

2.2.1. Architectural Characteristic in Turkish Bath 10

2.2.2. Heating System in Turkish Bath 12

2.3. Previous Studies about the Heating System of Historical Bath 15

2.3.1. Experimental Methods 15

2.3.2. Energy Analysis 16

2.3.3. CFD Methods 18

2.3.4. Floor Heating System 20

CHAPTER 3. MATERIAL.. 22

3.1. Material: Alibey Bath 22

3.1.1. Architectural Characteristics.. 28

3.1.2. Structure Date 29

3.1.3. The Heating System of the Alibey Bath 29

CHAPTER 4. METHODOLOGY 32

4.1. Geometry.. 33

4.2. CFD Simulations 35

4.3. Boundary Conditions 37

CHAPTER 5. RESULTS 43
5.1. The Heating System with Hypocaust.. 43
5.2. The Floor Heating System 77
5.3. Discussion 84

CHAPTER 6. CONCLUSION 88

REFERENCES 90

LIST OF FIGURES

Figure **Page**

Figure 1.1. The pool in the Alibey bath [3] 2

Figure 1.2. Oculus in Yeşil Direk Bath [3].. 2

Figure 1.3. Navel stone in Turkish bath [4].. 2

Figure 1.4. Location of Alibey Bath [5] 3

Figure 1.5. Top view of Alibey Bath [3] 4

Figure 2.1. Plan of Faustina Bath in Miletus [11] 8

Figure 2.2. Section of a relatively small size historical Roman Bath [13] 9

Figure 2.3. A schematic drawing of a historical Turkish bath [16] 10

Figure 2.4. Men part and women part of Lüks Bath [4] 11

Figure 2.5. Urla Özbek *Hamamı*, The copper boiler in the hot water tank [23]............ 13

Figure 2.6. Sığacık Kaleiçi Bath, The furnace [23] 14

Figure 2.7. A schematic drawing that shows the heating system of historical Turkish bath [20] 15

Figure 3.1. Plan of the Alibey Bath. (Scale: 1/200).. 23

Figure 3.2. West facade of changing room in the Alibey Bath 24

Figure 3.3. Courtyard... 25

Figure 3.4. Water storage room in the courtyard 25

Figure 3.5. Entrance on the east facade of the Alibey Bath. (Scale: 1/200) 25

Figure 3.6. A dome with wooden structure in changing room [3]................................. 26

Figure 3.7. Schematic plan of the Alibey Bath and routes 28

Figure 3.8. Hot Water Boiler 30

Figure 3.9. The Chimney 30

Figure 3.10. The Chimney 31

Figure 3.11. The Chimney 31

Figure 4.1. Drawings showing the construction of the ‘‘raised floor’’ of historical baths [20] 34

Figure 4.2. The hypocaust system of the Alibey Bath 35

Figure 4.3. The details of the hypocaust system in Alibey Bath 35

Figure 4.4. Polyhedral Mesh 37

Figure 4.5. The perspective of the hypocaust system and walls of the Alibey Bath 38

Figure 4.6. Scenario a 40

Figure 4.7. Scenario b 40

Figure 4.8. Scenario c 40

Figure 4.9. Scenario d 40

Figure 4.10. Floor heating system of the Alibey Bath [43] 42

Figure 4.11. Floor heating system [44] 42

Figure 5.1. Streamlines in the hypocaust for Scenarios a, b, c, and d 44

Figure 5.2. The velocity vectors in the hypocaust plan for Scenarios a, b, c, and d....... 46

Figure 5.3. The velocity vectors in the x-plane for Scenarios a, b, c, and d.................. 49

Figure 5.4. The temperature distribution in the hypocaust for Scenarios a, b, c, and d . 51

Figure 5.5. The temperature distribution in the hypocaust plan for Scenarios a, b, c and d 53

Figure 5.6. The temperature distribution on the walls for Scenarios a, b, c and d 56

Figure 5.7. The temperature distribution in the x-plane for Scenarios a, b, c and d....... 58

Figure 5.8. The temperature distribution in the x-plane for Scenarios a, b, c and d....... 60

Figure 5.9. The temperature distribution in the x-plane for Scenarios a, b, c and d....... 62

Figure 5.10. The temperature distribution in the z-plane for Scenarios a, b, c and d..... 65

Figure 5.11. The temperature distribution in the z-plane for Scenarios a, b, c and d 67
Figure 5.12. The temperature distribution in the z-plane for Scenarios a, b, c and d 69
Figure 5.13. The temperature distribution in the y-plane for Scenarios a, b, c and d 71
Figure 5.14. The temperature distribution on the floor for Scenarios a, b, c and d 73
Figure 5.15. The velocity vectors in the x-plane 78
Figure 5.16. The temperature distribution on the walls 78
Figure 5.17. The temperature distribution in the x-plane 79
Figure 5.18. The temperature distribution in the x-plane 80
Figure 5.19. The temperature distribution in the x-plane 80
Figure 5.20. The temperature distribution in the z-plane 81
Figure 5.21. The temperature distribution in the z-plane 81
Figure 5.22. The temperature distribution in the z-plane 82
Figure 5.23. The temperature distribution in the y-plane 83
Figure 5.24. The temperature distribution on the floor... 83
Figure 5.25. Prafurnium Temperature [13].. 85
Figure 5.26 Temperature variation [24]... 86

LIST OF TABLES

Table **Page**

Table 2.1. Compare previous studies as experimental methods 16
Table 2.2. Compare previous studies as energy analysis 18
Table 2.3. Compare previous studies as CFD methods 19
Table 2.4. Compare previous studies about floor heating system of A Chinese Kang .. 21
Table 4.1. Convective heat transfer coefficients and the related environment temperatures 38
Table 4.2. Building materials thermal conductivity values and their dimensions [42] .. 39
Table 4.3. Values of average thermal conductivity 39
Table 5.1. Mass flow rates in kg/s from the furnace (Inlet) to the chimneys (t1-t8) and mass flow rate fraction 75
Table 5.2. Amount of heat transfer rate in W from the furnace to the different sections of the bath 76
Table 5.3. Temperature value in °C in hot baths (H1, H2) and warm baths (W1, W2) 84

CHAPTER 1

INTRODUCTION

The heating systems of Turkish bath, specifically Alibey bath were investigated numerically from past to present by using CFD tool. Heated rooms of the bath were modeled and analyzed by the original heating system with different chimney configurations and the modern under floor heating system. For that purpose, an overview of this thesis is presented below in this section. The first of those sections is called "the argument" explains the basis of the study, while the second is called "the procedure" and it consists of the outlines and basic steps of the study.

1.1. Argument

The spatial representation of the action of bathing has passed through various levels for decades since prehistoric periods, established a basis for different architectural designs and become a significant part of daily life. Bath structures emerged during the Hellenistic period with importance in their era [1]. Romans who were influenced by the Greek bath structures improved these structures; and made the heating system applicable to private houses as well. Romans took baths as a part of daily praxis and turned them into social places. Roman baths were not only places for cleaning, but also carried sports activities, theatrical acts and games. Besides that, having both cool and warm pools and separating women and men sections for a period were what distinguished them from other baths. Along with that, there were times when it was prohibited for women and men to use baths at the same time, e.g. Hadrian period [2]. Turkish bath either has different sections for women and men or is used on different days or hours by each gender. The reason baths had great importance during Ottoman period was Islam's precision of cleanliness. Besides that, along with being a social place that people visit before customary activities, Turkish bath is used regularly. The reason people used it on a regular basis is there was no appointed place for cleaning in building designs in Ottoman and early republic period. Roman and Turkish baths are distinguished not only by their usage but also by their architectural attributes. During

Roman period, baths grew larger, covering massive areas like 100.000 m² with their sports centers. Caracalla bath in Rome, Faustina bath in Millet, Ankara Roman bath; however, places only related to bathing are 10.000 m² areas approximately. On the other hand as Turkish baths, Galatasaray bath and Ayasafoya Hürrem Sultan bath covered approximately 1300 m^2 area. In this area, the pool size and usage patterns in Roman and Turkish baths are different. In the Roman baths, there are large sized pools located in the open air and closed areas, but smaller sized pools usually are located in the heated areas. However, in Turkish bath cool pools are in small scales, located in the entrance and work only as a reflection source (Figure 1.1). Besides that, on Turkish baths at the dome, there is designed lighting windows called oculus (Figure 1.2) [3]. There is also a navel stone in the Turkish baths, which is different from the Roman baths. (Figure 1.3) [3]. Generally, one of the hottest surfaces of the bath is in the Turkish bath, where rubbing, washing and massaging are performed [4]. Moreover, marble slab (*göbektaşı*) is located in the center of the hot space which is called the heart of the bath [4].

Figure 1.1. The pool in the Alibey bath [3].

Figure 1.2. Oculus in Yeşil Direk Bath [3].

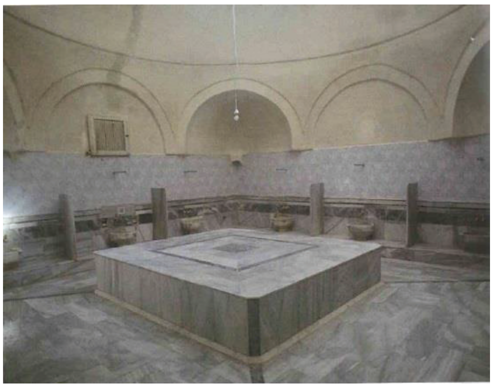


Figure 1.3. Navel stone in Turkish bath [4].

Some portions of Turkish baths are still used today. Many of them are heated with furnished pipes in which circulates hot water on the ground. Besides that, there are also some baths that use current hypocaust system heated with flue gas that is called "*cehennemlik"* in Ottoman period. Moreover, Turkish baths that dated to more recent time have designed with the floor heating system. From this point, by considering different boundary conditions, heating analysis of two different usage type in Turkish bath heating system carried accordingly in this thesis.

The study was conducted on a Turkish bath, a ''*hamam*'', Alibey bath, located in the city of İzmir, Turkey 38° 27´ 30.06"N and 27° 6´ 59.67"E (Figure 1.4) [3]. This structure is typical Turkish bath and consists of one part for man or woman. The bath represented the bath culture during Ottoman period and is used actively nowadays. The Alibey bath keeps original heating system's traces and architectural technologies. The Alibey bath was heated by a traditional heating system but nowadays the floor heating system is used. In the light of this information, the Alibey bath is chosen (Figures 1.4 and 1.5) [5, 3].

Figure 1.4. Location of Alibey Bath [5].

Figure 1.5. Top view of Alibey Bath [3].

The specific objectives of the study about the thermal analysis of the Alibey bath are:

- To define the mass flow rate of flue gas and flue gas inlet temperature and to calculate the heat transfer rates from the hypocaust to the heated spaces.
- To obtain the temperature distribution of the hypocaust system and the spaces of the Alibey bath. Also to obtain flue gas flow patterns at different sections of the bath.
- To evaluate the chimney configuration for the flue gas exhaust and the distribution of the heat flux at the floor in order to obtain the homogenous heat transfer rate through the bath floor and to estimate the system efficiency.
- To compare the hypocaust and the hot water circulation systems considering energy efficiency for the Alibey bath.

In the direction of these objectives, two heating system methods are compared; one of them traditional heating system which exhaust flue gas circulate along the hypocaust and the other heating system is under floor heating system heated by the hot water flow inside of the pipe which has wider applications recently.

1.2. Procedure

This study is represented in four sections. In the first, a literature survey is carried out about historical Roman baths and Turkish baths of the Ottoman period, in terms of their architectural characteristics and heating systems in Chapter 2. On the other hand, the traditional under floor heating system is examined for Kang houses in the northern China. Architectural characteristics and approaches of the historical bath are defined and heating system of the bath is also described in this phase.

In the second phase in Chapter 3, Turkish bath in Ottoman period, the Alibey bath, in İzmir, Turkey is described together with its heating system from past to present. Architectural characteristics of the Alibey bath is also defined in this section.

In the third phase, 3D simulation on ANSYS Fluent is created by using different chimney positions for Alibey bath in Chapter 4 namely "Methodology". The boundary conditions are defined for traditional with hypocaust system and under floor heating with hot water pipe system.

In Chapter 5, the results of the study were discussed in terms of the temperature distribution of the hypocaust and the different sections of the hot and warm baths in the historical Alibey bath for each chimney scenarios individually. The hot water circulation system was also investigated in the heated rooms of Alibey bath. The heat fluxes from the floor surfaces for different systems, namely hypocaust and hot water pipe systems, were also evaluated and discussed considering their energy efficiency.

In the light of these findings, the results of the study were evaluated and some recommendations were given for future studies in the conclusion chapter numbered 6.

CHAPTER 2

LITERATURE SURVEY

In this chapter, the literature survey of the study is presented. Firstly, Roman baths in Roman period are examined in terms of their architectural characteristics and heating system since Turkish baths are effected by historical Roman baths. Secondly, historical Turkish baths are summarized from the point of their architectural characteristics and the heating system. Then, many investigations are examined in the previous studies and some of them are compared each other about the heating system of the historical baths. Besides this, traditional under floor heating system is investigated in houses in northern China since this heating system has some similarities with the heating system of Turkish bath.

2.1. Roman Bath

Roman bath spreads over the whole Roman Empire. Therefore, many researchers define the Roman bath as large public complexes and public or private smaller-scale facilities. Furthermore, baths have an important role in the Ancient Rome, because they used to represent a symbol of power, wellness and lifestyle. According to Yegül, Roman bath describes the ideal Roman urban living [6]. A Roman bath is a step in the process of the civilization of Roman Empire. In addition to this, the Roman bath was not merely used for cleaning, they served for people's amusement and enhancing social relations as well. They held many opportunities for several activities: cold, warm and hot baths, physical activities, cultural events, food etc. Moreover, the Romans experienced the state-of-art architectural approaches, improving the heating system technologies to circulate heat through a floor and within the walls. Additionally, most essential innovations were used to improve this heating system in the Roman bath.

The definition of the design principles of the historical Roman bath was given in the study of Vitruvius. According to him, when Roman bath was designed, heated rooms were located in the southern part of the bath, while unheated rooms were located in the northern part. He claims the heated chamber to have been separated from the unheated chamber. In addition to this, the main openings were located in the southern facades, whereas small openings such as windows were located in the western fronts. When all things are considered, these approaches are the current principles of the low energy usage in the buildings as the passive solution methods [7].

2.1.1. Architectural Characteristics in Roman Bath

Bath and bathing extend over the earliest civilizations and houses or cities have separate structure for bathing in the architecture of almost every civilizations. Furthermore, bathing in antique times served not only for cleaning but also as a landmark for social interaction and entertainment [8].

The Roman bath is composed of many parts for different purposes. One of them is *apodyterium*, which stands for changing room and is the largest room of the baths. In addition to this, it is used for waiting and resting and in some baths, it is connected with the entrance. Another part of the Roman bath, which serves as a cold bath, is called *frigidarium*. The center of *frigidarium* locates a pool called *natation* or *piscine* - depending on whether it is inside or outside, which is filled with cold water. Furthermore, there is a warm bath which is called *tepidarium*, and usually, it is designed between cold and hot baths. This section is used for oiling and massaging if there is no other space in the rest of Roman bath for these purposes [9].The last part of the Roman bath is *caldarium*, which is the hottest bath. *Caldarium* has the highest temperature in the Roman bath if there is not another special bath section called *lucanocium* or *sudatorium* which is designed relatively smaller and used for sweating like today's fin saunas. In addition to this, some baths are located near a gymnasium for playing games and sports activities [10]. The plan of a typical historical Roman bath is given in Figure 2.1 [11].

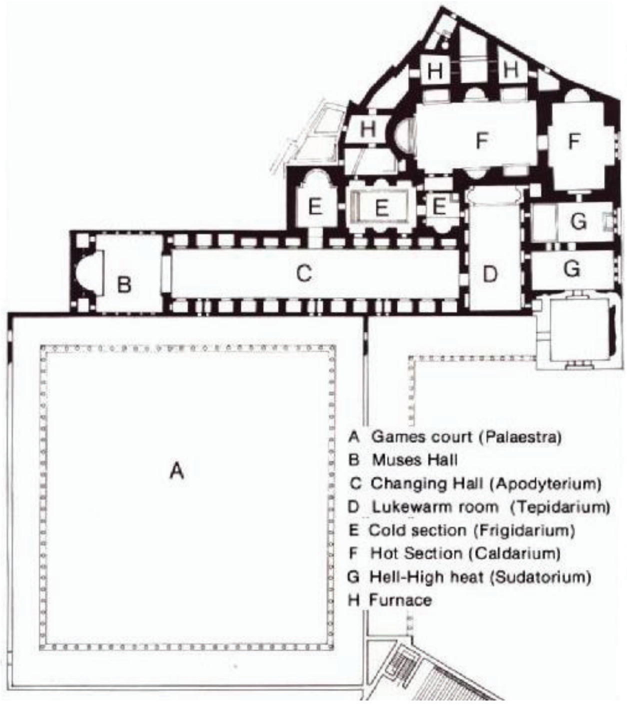


Figure 2.1. Plan of Faustina Bath in Miletus [11].

As Carcopino states, the Roman bath was opened in days in Rome in the first century AD but outside of Rome, at nights as well. In early of Roman bath usage, men and women's used all parts together but then it was forbidden by Hadrian because of social interventions. After that, they were used separately at the individual parts of the baths [2]. As Carcopino also states, a gymnasium-bath complex was common in Anatolia as the Hellenic gymnasium. Moreover, these baths were used in Anatolia in the Byzantium period. The Turkish bath got affected by this structure and a new tradition is launched under the Byzantine influence [12].

2.1.2. Heating System in Roman Bath

The definition of the heating system of historical Roman bath was given in the study of Akok [12].The hypocaust system supports are provided by quadrilateral or cylindrical brick or limestone. When wood is burned in the furnace, existing gas circulate throughout all hypocaust system and also warm up the rooms of the bath. In addition to this, existing gas circulates through the chimneys placed at the corner of the wall and hot flue gas leaving chimneys. At the same time many walls of baths are heated by this method, the structural element is called *tubuli* which is made of brick and these *tubulies* are located between the internal and external walls of the bath. In Figure 2.2 shows the sections of a relatively small size historical Roman bath [13].

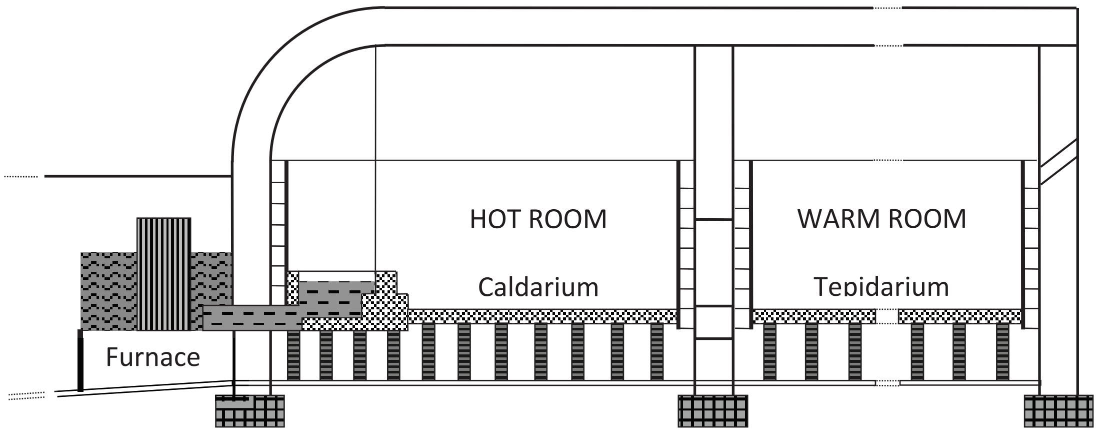


Figure 2.2. Section of a relatively small size historical Roman Bath [13].

2.2. Historical Turkish Bath in the Ottoman Period

Turkish bath was widely-used and spread all over Anatolia under the rules of Islam's precision of cleanliness. Historical Turkish bath was designed according to typical-characteristics of the Anatolian-Islamic bath throughout the Ottoman Empire. Caner and Saltık claim that historical Turkish bath also reflects the architectural and technological knowledge of the Hittite period and bathing culture in Anatolia [14].

After the Turks had arrived at Anatolia, they got acquainted with the small public baths of Byzantine cities due to the fact that Roman bathing culture was spread all over Anatolia during the Byzantine period. Temizsoy et al. also supports this idea by saying that existing culture, architecture and technology of baths in Anatolia were combined with cleaning tradition of Islam. As a consequence, new buildings for bathing were designed and a new tradition was created that would later be named as 'Turkish Bath' or *'hamam'* [15].

Işık explains that the bath tradition was originated in the 16^{th} century in the Ottoman Empire. Moreover, the bath reaches an irreplaceable part of the urban living, thanks to the administrations of the public organizations [8]. Çakmak [16], Önge [17], Taşcıoğlu [18] and Işık [8] state that the historical Turkish bath served to two groups as public and private in Anatolia. In a study of Önge, some baths served a small group of people, generally, people of formality such as palace, military barracks or caravanserais, other baths served to the public for people living in a village, a district or a part of a city [17].

According to Taşçıoğlu, the historical Turkish bath was constructed as single bath or double bath they referred as public bath (*halk hamamı*) and bazaar bath (*çarşı hamamı*) Furthermore, a single bath was designed for men or women and was called mid-morning bath (*kuşluk hamamı*), where men and woman used the bath separately on different days and hours. In addition to this, a double bath was open for men and for women which were placed side to side and their management systems were separated but their service system was the same [18]. Önge states that the man parts of the historical Turkish bath are larger than woman parts. However, the entrance of man's part of the historical bath was from the main street, the entrance of women's part was from the side street for more privacy [17]. In addition to this, Önge determines some bath that is called geothermal baths in Anatolia, this bath was established on hot water sources. This geothermal bath was generally used for curative purposes rather than bathing [19].

2.2.1. Architectural Characteristics in Turkish Bath

The historical Turkish bath consists of three main parts of their construction. These parts are changing section, bathing section and service section. The planning scheme of typical historical Turkish bath that shows the organization of the spaces is given in Figure 2.3 and Figure 2.4 is also given for an example of different sections of woman and men. [16].

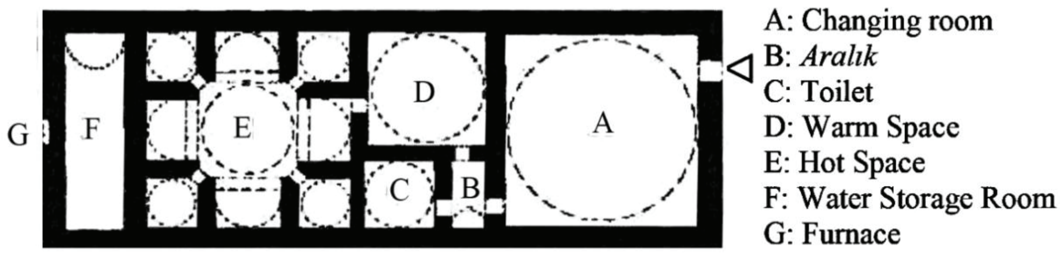


Figure 2.3. A schematic drawing of an historical Turkish bath [16].

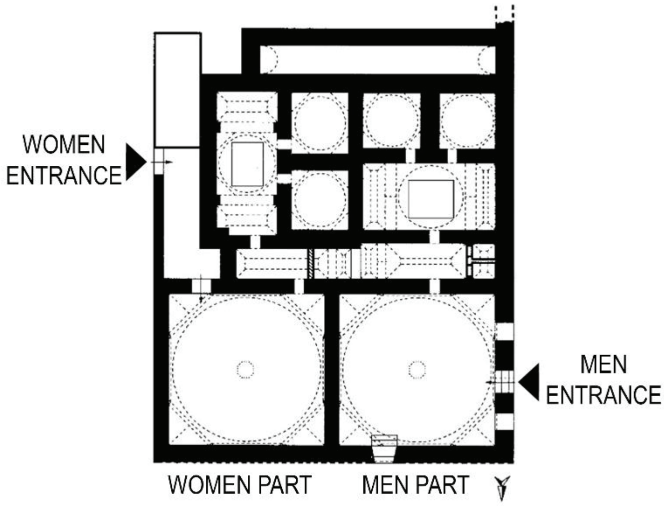


Figure 2.4 Men part and women part of Lüks Bath [4].

However, the main entrance is changing room in the historical Turkish bath as shown as A in Figure 2.3 and indicated. However, changing rooms do not use for entrance in some Turkish bath. Thus, another space is created for the entrance to provide to control of the interior climatic conditions and privacy. Changing spaces of the historical bath have generally high massive walls that are covered by dome or roof with a window to enlighten the space [15]. The characteristics features of this section are to raise balconies and to provide two-story wooden galleries for clients to change their clothes inside of the bath. In addition to this, there is a coffee serving section for creating a place for relaxation after bathing for clients and there is a small pool for an ornament in the middle of this section.

As Aru noted, the purpose of the warm bath (*ılıklık*) (indicated as D in Figure 2.3) that is to provide a transition zone before entering to a hot bathing area so that the body temperature can adapt to temperature difference while passing to the hot space mentioned in Figure 2.3 [16]. Another purpose of this space is to provide a refreshing and resting area between changing room and hot bath [20]. Warm bath is covered with dome or vault which can be rectangular or corridor shape. Shaving room and toilets (in Figure 2.3) do not locate in this part; it locates in a place where connects with the warm or hot bath. In addition, another part of the bathing section is the hot bath indicated as E which is the hottest part of the bath and it is the place where bathing activities take place [15]. Definition of the hot spaces in the historical Turkish bath is given in the study of Önge [17]. According to her, *iwans* (*eyvan*) and small bathing cells are located in the hot spaces. Moreover, navel stone (*göbektaşı*) is located in the center of the hot space which is called the heart of the bath [17].

Taşçıoğlu says that in the examples of the Turkish bath in Anatolia, there is a space which is called *aralık* mentioned as B between the changing room and bathing sections that is consisted of toilets and depilatory cells [18]. In a study of Önge, most important thing is that is provided to control heat transfer between hot and cold spaces in Anatolian baths, is prevented the leakage of the hot air and steam from the bathing section [17]. Aru states that in later examples of the Turkish bath, the changing and bathing sections are divided by the door to control heat loses [20].

The last part of the historical Turkish bath is the service sections. In a study of Dişli, service sections consist of hot and cold water storage room, firewood storage room, furnace and hypocaust (*cehennemlik*) which is similar to the hypocaust system in the Roman bath. Water is stored in the hot and cold water storage room indicated as F and the furnace mentioned as G (Figure 2.3) is located under the hot and cold water storage room to heat water. This room is located one side of the hot bath. The hot water tank has a small opening such as a window on the wall adjacent to the hot bath which is called an observation window [21]. Moreover, the purposes of these openings are to control the amount of water in these rooms, provide water and repair the section if it is necessary [17].

Another part is the firewood storage room where the fuel is stored for heating of the bath. In the historical bath, the wood is burned in the furnace and concave copper boiler which is located over the fireplace thus water is heated by fire in the hot water tank. Moreover, the hypocaust and draft chimneys (*tüteklik*) are the elements of the heating systems. Flue gas results from the burning up of wood circulate inside the system and go out from the draft chimneys then the interiors of bathing spaces are heated.

2.2.2. Heating System in Turkish Bath

There are some studies about the heating system of historical Turkish baths. First of all, in the study of Yegül, the plan scheme and organization plan in the historical bath is related to the heating system of a bath. The heating system development depends on directly on the organization of spaces. Moreover, in these buildings, it is clear to see plan organization such as serving and served spaces [22].

According to Önge [17], while the historical bath is designing, plan organization is important in order to increase the efficiency of the heating system.

Temizsoy et al. [15] further explain that the definition of the heating system of the Turkish bath in his study as Önge [17] and Yegül [22] does. Water, hot water tank, hot bath and warm bath are used the same heating system in the historical Turkish bath. The water is heated by the fire provided from burning of firewood in the furnace located in the storage room. Moreover, the copper boiler is positioned just over the fire which helps to heat the water in the tank [15, 17 and 22]. Fire is burned through an arched opening that stands under the hot water tank as shown in Figure 2.5 [23].

Figure 2.5. Urla Özbek *Hamamı*, The copper boiler in the hot water tank [23].

According to Önge, the historical bath is heated by burning of firewood inside the furnace that means hot flue gas moves through the hypocaust system by free flow under the buoyancy effect created by the density gradient which is induced by temperature differences. The spaces of the historical bath are heated by this flue gas [17]. Temizsoy et al. further explains the definition of "raised floor". The hypocaust is composed of layers; one of them is a slate stone that is covered by a layer of mortar. These layers are bedding for marble slabs thus hot air does not come into the marble slabs [15].

The boiler that is heated by burning fire starts to heat water. The heated water is transmitted through with terracotta water pipes to wash basins (*kurna*). There is a space underneath the floor of hot bath (*sıcaklık*) called hypocaust. This space includes short earthen columns in griddle order Furthermore, in the Alibey bath hot water storage was a small opening on adjacent hot space wall in order to control vapor. The furnace under the hot water tank and hypocaust system could not be observed since the ground is filled (Figure 2.6) [23].

Figure 2.6. Sığacık Kaleiçi Bath, The furnace [23].

The circulation system of flue gas in the hypocaust was given in a study of Önge [17] According to her, flue gas circulates throughout the hypocaust exit inside of draft chimneys inside of the wall. Temizsoy et al. also state that the chimneys are made of terracotta vertical pipes and they are located as holes inside of the massive rubble stonewalls [15].

The pressure of hot flue gas circulation in the hypocaust is provided by opening and closing dampers the tops of these chimneys. Furthermore, chimneys inside of the exterior wall provide heating at the same time. They control of heat transfer and heat loss inside of the bath (Figure 2.7) [20].

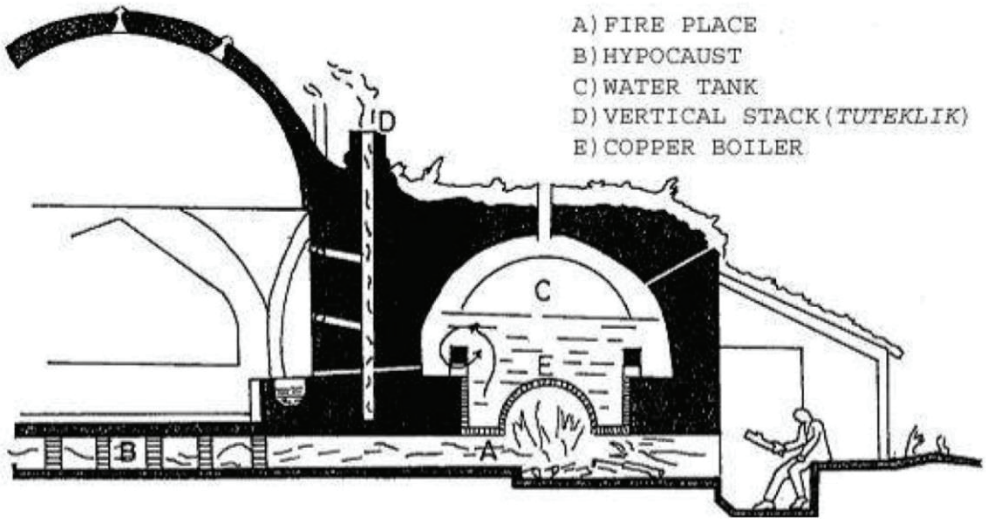


Figure 2.7. A schematic drawing of the heating system of historical Turkish bath [20].

In the historical bath, the navel stone is elevated from floor slab is located in the middle of the hot space, the navel stone is the hottest surface of the bath. Many studies are making surveys about the heating system of the historical bath by researchers, these surveys are limited on the efficiency and capacity of the heating system. Especially there is not any study about the thermal analysis of the heating system of the historical Turkish bath, to the best of the author's knowledge.

2.3. Previous Studies About The Heating System of Historical Baths

Traditional and historical floor heating systems were already investigated in the literature. These studies were mainly analyzed thermal environment of Roman bath and traditional Chinese *kang*. In the literature, some studies have mainly included experimental works; some of them are focused conventional energy analysis and CFD simulation is used in the other part of the studies. These studies have been examined in this section by subdividing them.

2.3.1. Experimental Methods

Kretzschmer [13] and Hüser [24] have experimental study about bath's heating system. The first detailed study about Roman Bath was made by Kretzschmer.

Kretzschmer and Hüser studied the flue gas temperature over the hypocaust in graphical forms and these studies based on experimental data on baths. Kretzschmer also made temperature measurement many points of the bath, defined isotherm and calculated the amount of heat transfer as 2 kW comes from the hypocaust system. Kretzschmer claimed that the flue gas temperature which was the outlet from the furnace *praefurmium* was around 150°C. Hüser made another experimental study on bath by using the same bath with Kretzschmer. Moreover, he stated that the gas temperature under the floor was around 65°C and floor temperature was 27°C. On the other hand, Hüser also recorded the same temperature which was 150°C exit from *praefurmium* based on Kretzschmer's study. He determined average temperature was 18°C on the floor while it was 38°C the floor near to the furnace. Moreover, Hüser examined measurement change flue temperature in time and defined temperature distribution on the floor and the wall (Table 2.1).

Table 2.1. Previous studies as experimental methods.

References	**[13]**	**[24]**
Location	Saalburg GERMANY	
Heated rooms temperature values	Flue gas temperature is 150°C exit of the *praefurmium.* Flue gas temperature is 60°C – 63°C under the floor. Floor Temperature is 27°C.	Flue gas temperature is 150°C exit of the *praefurmium.* Floor temperature is 27°C Temperature is 38°C on the floor near the furnace.

2.3.2. Energy Analysis

In many studies, there are different results of thermal conditions in bathing complexes. Thatcher [25], Rook [26], Jorio [27] and Başaran [28] carried out thermal analysis of bath's heating system under steady-state working condition. Thatcher reconstructed five rooms of forum bath at Ostia in Italy and he defined that the hot surfaces of the warm rooms were seen to be close to 40°C. Moreover, he stated that windows did not require the glazing in the forum baths at Ostia and he created table relating to room thermal condition [25]. On the other hand, Rook accepted external environment as 10°C in his study and he calculated amount of firewood as 114 ton per year for keeping *caldarium* room 70°C and *tepidarium* room 55°C under the condition of being 220°C flue gas temperature, but over an area of only 15 m². When Rook made calculations about these issues, he acknowledged that furnace burned all year [26]. Jorio analyzed the caldarium of the Stabian baths and he said that 7 kg of wood per hour was needed to maintain a constant internal temperature is 35°C for heat room covered 114 m² [27]. In addition to this, Başaran and Ilken studied small bath in ancient *Phaselis* located southwest of Anatolia. After this numerical study, they reached some temperature values about heated surfaces of the bath which heated walls were around 45°C in the *caldarium,* 29°C in the *tepidarium* and 65°C in the *sudatorium.* The Temperature was approximately 58° on the floor in the *caldarium* and around 34°C on the floor in the *tepidarium.* Moreover, they estimated that fuel consumed by the baths in *Phaselis* was about 15 kg/h for footprint area of 107.63 m² [28].

All considering these studies, it was mentioned that the temperature of heated surfaces such as floors and walls were between 27°C and 65°C, while the average flue gas temperature was recommended between 60°C and 220°C in the hypocaust. Furthermore, studies reports were examined and fuel consumption spans about between 6.0 and 15.0 kg/h, and the efficiency of 10 to % 43 (Table 2.2).

Table 2.2. Compare previous studies as energy analysis.

Research	[25]	[26]	[27]	[28]
Location	Ostia ITALY	Welwyn ENGLAND	Pompeii ITALY	Antalya TURKEY
Heated rooms temperature values	Hot surfaces of the warm room are 40°C.	Flue gas temperature is 220°C in the hypocaust. *Caldarium* temperature is 70°C. *Tepidarium* temperature is 55 °C.	Internal temperature is 35°C.	Heated walls are 45°C in the *caldarium.* Floor temperature is 52.6°C – 64.6°C in the *caldarium.* Heated walls are 29°C in the *tepidarium.* Floor temperature is 31.7°C – 36.7°C in the *tepidarium.* Heated walls are 65°C in the *sudatorium*.
Amount of fuel		13 kg/h Firewood	7 kg/h firewood	15 kg/h firewood
Foot print Area		15 m²	114 m²	*Sudatorium* is 9.16 m² *Caldarium* is 60,50 m² *Tepidarium* is 37,97 m²

2.3.3. CFD Methods

In order to evaluate the thermal conditions, different baths are researched. Some of them are the Indirizzo Baths of Catania [29], the Caldarium of the Roman Bath in Sardis [30] and two caldarium sections in Metropolis [31]. The accuracy of fluid dynamics simulations needed a precise representation of the 3D geometry of the selected environment and the characterization of the construction materials, as well as the definition of the appropriate boundary conditions. Substantially, through a CFD analysis, they simulated the heat transfer from the hypocaust − where the hot gases of the furnaces pass before exhausting through the chimneys − to the caldarium.

The Indirizzo baths of Catania at Sicily in Italy was analyzed numerically by using a CFD tool [29]. They modeled hypocaust system of the bath. Thus, 11 circular bricks were located hypocaust and their height was 75 cm, a diameter was 24 cm, a thickness was 6.5 cm. Moreover, the 3D grid was of the CFD environment constituted by a total of 149,232 nodes and 842,946 tetrahedral elements. At the end of the studies, they claimed that temperature was around 37°C in the *caldarium* and floor’s temperature was around 45°C in the *caldarium* [27].

Oetelaar et al. [30] analyzed the Caldarium of the Roman Bath at Sardis in Turkey. The 3D grid was constituted by a total of 1,976,183 cells. They stated that temperature was around 37°C in the *caldarium* and floor's temperature was around 43°C in the *caldarium*.

Başaran et al. studied the Caldarium of the Roman Bath at *Metropolis* in Turkey. After these studies he reached some temperature values about bath which wall's temperature was around 45°C and floor's temperature was between 31.7°C and 36.7°C in the *caldarium* and wall's temperature was 65°C and floor's temperature was between 52.6°C and 64.6°C in the *tepidarium* (Table 2.3) [31].

Table 2.3. Compare previous studies as CFD methods

Research	**[29]**	**[30]**	**[31]**
Location	Sicily ITALY	Sardis TURKEY	Metropolis TURKEY
Hypocaust	Height is 75 cm 11 circular bricks Thickness 6.5 cm Diameter 24 cm Hot gas temperature is 130 °C.		
Heated rooms temperature values	Temperature is 37°C in the *caldarium*. Floor surface temperature is 45°C in the *caldarium.*	Temperature is 37°C-38°C in the *caldarium*. Floor surface temperature is 42°C-44°C in the *caldarium*.	Wall's temperature is 45°C and floor surface temperature is 31.7°C-36.7°C in the *caldarium*. Wall's temperature is 65°C and floor surface temperature is 52.6°C-64.6°C in the *tepidarium*.
Geometry	149,232 nodes 842,946 tetrahedral elements	1,976,183 cells	
Boundary Condititons	Four different scenarios May 15th 20°C Concameratio in the *caldarium* or not January 15th 10°C Concameratio in the *caldarium* or not	Five important sub-models: time dependency, density, turbulence, multi-phase, species.	The air temperature is 0°C. The natural convection effect had not been considered inside. There was no heat transfer at the wall from the semicircular areas of the bath.

2.3.4. Floor Heating System

The Chinese Kang is a traditional heating system in the northern rural of China, this heating system provides local thermal comfort to peoples' living spaces. The traditional Kang, flue gas is laid up under the floor which is made of bricks of high thermal mass and then, flue gas exhaust from the chimney. When fuel is burned in the furnace, released hot gases recirculate under the floor before exhausting through the chimneys. Moreover, the kang body absorbs driblet of the heat of hot gases and it transmits heat of high-temperature smoke to the Kang surface gradually. As a result, the Kang create a comfortable local thermal environment. Many studies carried out by the researchers to develop dynamic thermal process and thermal environmental in the Kang (Table 2.4).

Firstly, Wang et al. studied on the rural houses with traditional Kangs in northern China [32]. They reconstructed mathematical model to examine temperature values and distributions on the traditional heating system. After finding results, they reached that the average temperature was between 21°C and 35°C on plate surfaces, air temperature rose up from 30°C to 45°C in under floor and inlet temperature increased from 17°C to 32°C during the measurement period [32].

Moreover, Gao, et al. [33] investigated dynamic analysis of the indoor thermal environment of rooms in Qinmao Village. According to their data, the indoor air temperature could reach up to 24°C, when the outdoor temperature was between -0.9°C and 10.3°C and plate surfaces temperature was 45°C during 9^{th} and 11^{th} January [33].

In addition, Wang et al. made another research about the traditional heating system of Kang houses [34]. According to this research, the inlet smoke temperature of wall body could be 60°C to 140°C, in order to that interior surface of the heated wall was maximum 55°C. In this study, the exterior surface temperature of heated wall measured between 20°C and 40°C. This showed that the room temperature fluctuated as well as the surface temperatures of the heated wall body [34].

Besides this, Zhuang et al. [35] investigated temperature values on a mathematical model in Dalian. In this research, kang house's plate surface temperature measured between 20°C and 35°C and indoor air temperature a half-elevated kang defined between 15°C and 20°C [35].

Table 2.4. Compare previous studies about floor heating system of A Chinese Kang.

Research	[32]	[33]	[34]	[35]
Location	In northern China.	In Qinmao Village, China.	In Beijing, China.	In Dalian, China.
Floor Heating System	16 reinforced concrete pillars. Each pillar diameter was 0.01 m and depth was 0.07 m.	Simple three-bays. Their heights were 2.7 m.	Wall body which was made of brick. Walls dimensions were 1.5m - 2.5 m long, 1.0 - 1.8 m high and 0.3 m wide.	Nine slabs (1 m x 0.60 m x 0.05 m). Slabs located on several columns (0.40 – 0.60 m).
Heated rooms temperature values	Plate surfaces temperature was between 21°C-35°C. Air temperature rose up from 30 °C to 45°C in under floor. Inlet temperature increased from 17°C to 32°C.	Plate surfaces temperature was about 45°C. Indoor temperature was between 16°C - 24°C.	The inlet smoke temperature of wall body was 60°C to 140°C. Exterior surface temperature of heated wall was between 20°C-40°C. Interior surface temperature of heated wall was maximum 55°C.	Kang plate surface temperature was between 20°C - 35°C. The indoor air temperature a half-elevated kang was 15°C - 20°C.
House Geometry	12 m long x 4m wide x 2.7 m high. External wall was 0.40 m, internal wall was 0.12 m.	4 m long x 3.7m wide x 2.7 m high. External wall was 0.40 m, internal wall was 0.15 m.	Only constructed heated wall in heat transfer model.	3 - 4 m long x 1.8 - 2.0 m wide x 0.6 – 0.7 m high.
Measurement Conditions	From February 28th to March 6th. Outdoor temperature was between 7°C – 10°C.	From January 9th to January 11th. Outdoor temperature was between -0.9°C – 10.3°C.	From December 18th to December 24th. Outdoor temperature was between 5°C – 10°C.	From November 11h to December 30th. Outdoor temperature was between -10°C.
The Heating Power	Ranged from 625W to 1170 W. Average value was 950 W.	-	Heat storage of chimney was 77,3 kj/s.	Heat rate of faceplate was between 543 kj -602 kj.

CHAPTER 3

MATERIAL

In this chapter, the Alibey bath is chosen as a material. Firstly, Alibey bath's geometry is examined in terms of their architectural characteristics. Secondly, Alibey bath is summarized from the point of the heating system past to present and the heating system is foreseen for this study.

3.1. The Alibey Bath

The Alibey bath is located on the street 1671 of Karşıyaka, a promise of İzmir, with a door number of 88. The Alibey bath doesn't have a planning scheme with two separate sections for men and women. Therefore, the bath is consisting of 4 main sections that go by the name of changing room, hot baths (H1 and H2), warm baths (W1 and W2) and hot water storage room (Figures 3.1). The planning scheme is arranged depending on the area while going through changing room, hot and warm bath. In addition to that, due to the street passing by the bath, the changing room is shaped into a trapezoid. Because of having the main entrance on it, the south facade is formed parallel to the street (Figure 3.2).

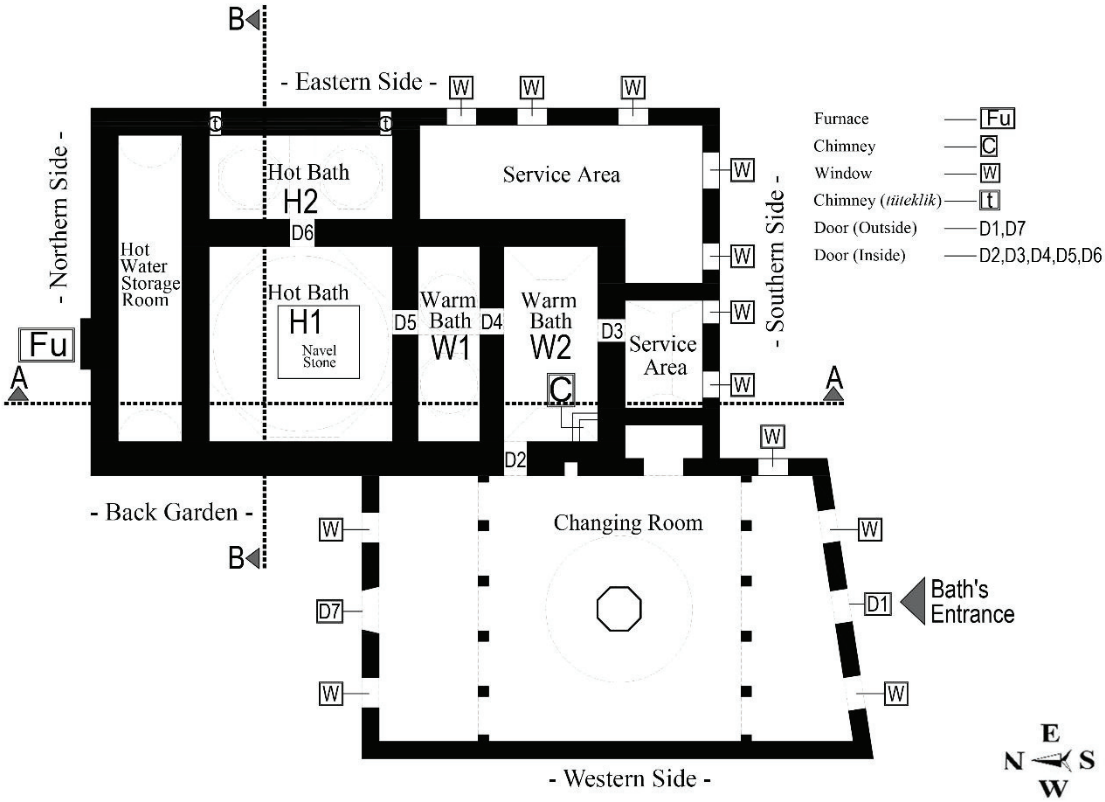


Figure 3.1. Plan of the Alibey Bath. (Scale: 1/200)

There is a molding on the entrance gap with an arc and a circular. Two rectangular windows are located on each side of the bath entrance. Metal shutters are assembled on the circular window and two rectangular windows each of which have a linear molding. Additionally, the traces of older structural materials are worn off due to the fact that the south façade of the changing room is plastered and painted with modern materials. The west façade of the changing room is blocked with following built up structures.

Figure 3.2. West facade of changing room in Alibey Bath.

The north façade of the bath is open to a courtyard that is bordered with the hot water tank and the furnace. The north façade of changing room is consisting of window and door openings of the same size as the ones on the south façade of the changing room. The circular window located above the bath’s entrance on the south façade is also exist on the north façade of changing room. Although the main structural material of the north façade is stone, the circular windows are constructed of brick. Due to the fact that there are barracks next to the west façade of a hot water tank, the structural material is not perceived (Figure 3.3). In addition to that, there is a water storage room out of date in the courtyard on the north façade (Figure 3.4.).

Figure 3.3. Courtyard

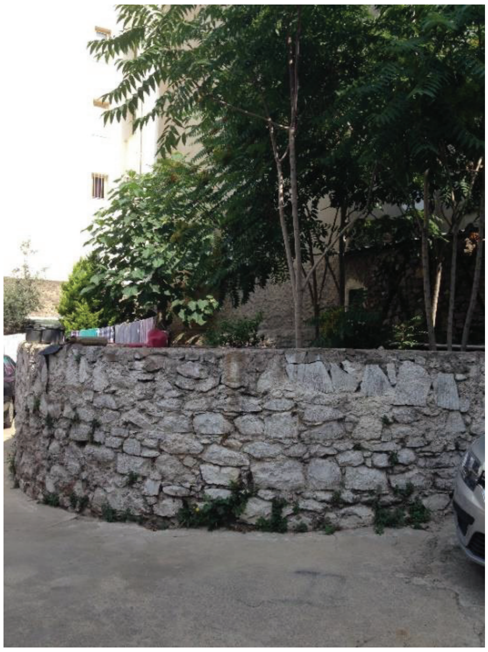


Figure 3.4. Water storage room

An L shaped space mentioned as service area (Figure 3.1) that inhibits warm baths on the south and east facades is located. This space has walls are thinner compared to the rest of the walls. Door and window openings on the south façade of this space are covered with bricks. It was not possible to get in this L shaped space which keeps the purpose unclear. It is not recognized whether it was constructed formerly or as an addition. There is an entrance gap on the east façade that is not used anymore today (Figure 3.5).

Figure 3.5. Entrance on the east facade of the Alibey Bath.

The changing room is formed of three parts. There is a sub floor that is carried with wooden studs placed in N-S axis on the north façade of changing room. These studs are connected to each other with arcs. Changing cells ordered in N-S direction are to be found on this sub floor. It is possible to reach these changing cells with u-shaped stairs on the north façade of changing room.

In addition to that, a dome with wooden structure is located in the middle of the changing room. The wooden dome is carried with 8 wooden studs with square profile located in N-S direction. The dome holds a circular skylight. There is an octagonal pool under the skylight (Figure 3.6).

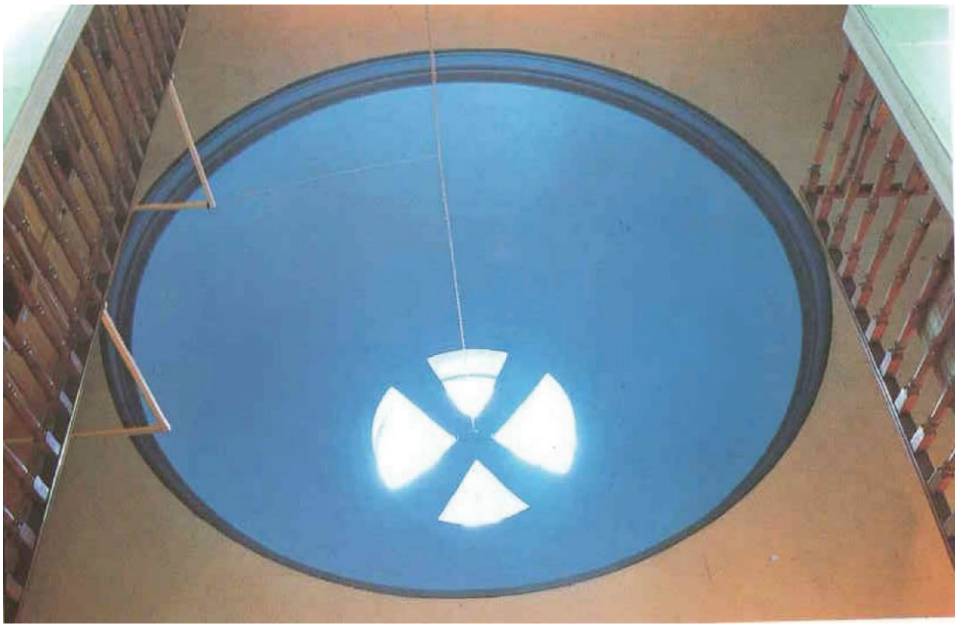


Figure 3.6. A dome with wooden structure in changing room [3].

The warm bath (W2) is entered through the opening numbered D2 in figure 3.1, from changing room, it is covered with a rectangle shaped cloistered vault. Moreover, there is a niche with low height arc between these two openings. A chimney is located on the west facade of this warm bath due to the heating system that was built afterward.

Another square planned space is entered through the opening (70 cm) numbered D3 in figure 3.1 which holds a low height arc on the south façade of the warm bath (W2). The construction time of this square planned space is unknown. It is presumed that this place serves as *keçelik* in service area providing that it was built in ancient. It is recognized which keeps the purpose toilet and *traşlık* in the service area at present time.

Also, the square planned are covered with a rectangle shaped cloistered vault such as a warm bath.

In addition to this, another square-planned space that is named warm bath (W1) (5.80 x 1.85 m) is entered through the opening numbered D4 in figure 3.1 (80 cm) on the north façade of the warm bath and the opening holds a low-height arc. This warm bath has a rectangle-shaped plan that is divided into two parts by an arch so that the warm bath consists of two square-plan schemes. Moreover, two square-plan spaces are covered with domes on each of them and these domes hold circular highlights. Additionally, basin and resting spaces are located at the corner of the warm space. On the other hand, the hot bath (H1) is entered through the opening numbered D5 on the north wall of the warm bath, which has again square-plan scheme and is covered with a dome, such as the warm bath. Also, this dome has a circular skylight. Furthermore, navel stone (2.65 x 2.18 m) with square-plan is located in the middle of the hot bath (5.80 x 5.45 m) right under the dome and basins are located along the walls of the hot bath.

On the other hand, hot bath has a rectangle opening numbered D6 in figure 3.1 with 80 cm width on the east façade, which leads to the space that is used as the hot bath (H2) as well. In addition, hot bath (5.45 x 2.50 m) and the hot bath share the same plan scheme and basins and resting space are located at the corners of walls in both places. Although hot (numbered 8 in Figure 3.7) bath has a rectangle shaped plan, it is covered with two domes of the same size individually. The east wall of the hot bath with a rectangle plan scheme has opening forming a window. The opening allows vapor to pass through a water reservoir. This opening has recently been covered by a wall (Figure 3.7).

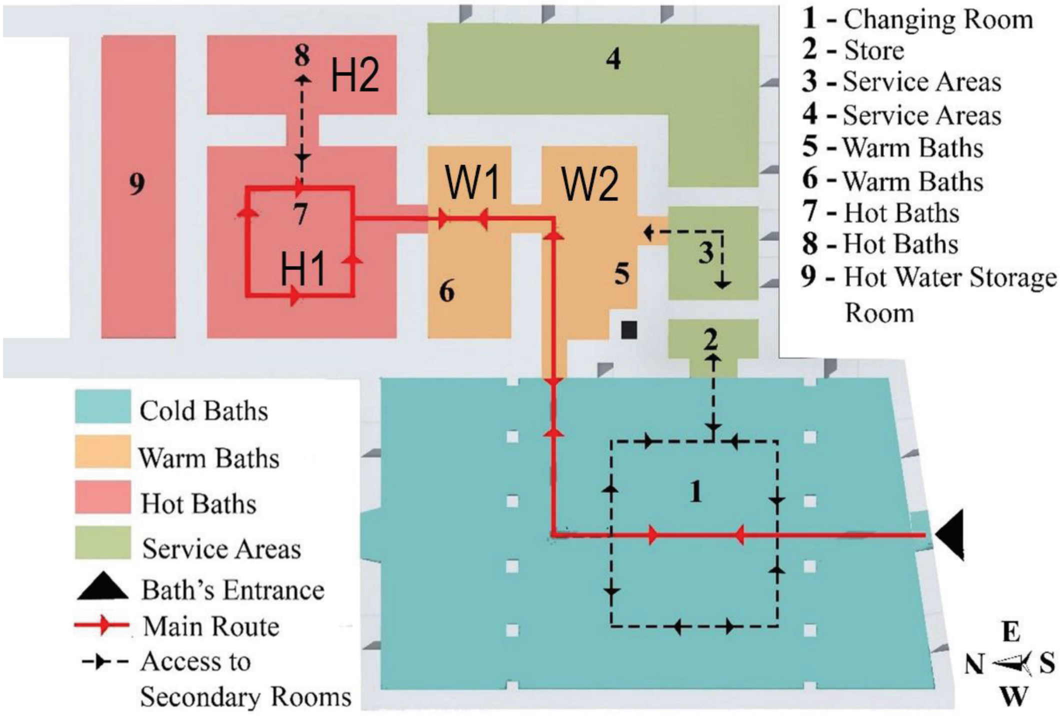


Figure 3.7. Schematic plan of the the Alibey Bath and routes.

3.1.1. Architectural Characteristics

The traces of older structural materials have been worn off in changing room's façade in the Alibey bath due to the fact that changing room façades are plastered and painted with contemporary materials. The dome of the bath is renewed in 20th century. Therefore, no one reaches any information regarding form and location in a former way.

In addition, areas of changing room are bigger than the rest of the spaces' in the bath. Unlike numerous historical baths in Ottoman Empire, this warm bath areas have rectangle plan scheme that is covered with a vault, which is rarely seen [3]. Furthermore, this warm bath is only named warm bath because of the fact that it connects hot bath, warm bath, hot water storage and toilet. According to Ürer, this rectangle space is located on the south side of the warm bath which holds toilet today, yet indicates signs of the older structure. This rectangle space is considered to be the most suitable function for *keçelik* in Figure 3.7 [3].

An L shaped space numbered 4 in figure 3.7 is located on the south and east facades in the warm bath and there is no connection to main bath walls. Because the L shaped façade had been plastered and painted, connecting line tracks have disappeared and it is considered to have been built at the same time with formerly. All information about the L shaped space considered, no one reaches any certain information about when the L shaped space has been constructed.

According to his researchers; Ürer gave some examples -depending on the fact that Alibey bath holds a hot bath with square scheme plan and a warm bath with rectangle shaped plan that is divided into two part by an arch. These are Bursa İnegöl Bath, Sinan Bey Bath, Edirne Sokullu Mehmet Paşa Bath Women Part (middle of 16th century), Aydın Cemal Bey Bath (beginning of 18th century), Kütahya Küçük Bath Man Part (early 15th century), Kütahya Şengül Bath (late 16th century) [3].

3.1.2. Structure Date

It is not possible to point out when the bath was constructed exactly since no epitaph is found inside the bath. However, the bath was taken over and run in 1972 by an anonymous individual who claimed that the Alibey bath was constructed in the 17th century by the Italian architect Gonzale Andriye, although no further information about the Italian architect constructing the Alibey bath was found. The Alibey bath was named after Alibey who first run the bath [3].

Taking previous analyses of baths into consideration, Ürer states that many historical baths sharing the same plan scheme as the Alibey bath were constructed between 15th - 18th century. It is appropriate to say that the changing room of Alibey bath was renewed and incorporated into the bath [3].

3.1.3. The Heating System of the Alibey Bath

The Alibey bath is used nowadays as a bath so the heating system of the bath is floor heating system with circulated hot water through the pipe system. Even if the Alibey bath still has some traces for the traditional heating system of Ottoman Period, this heating method does not use in nowadays. There is the floor heating system over the traditional heating system without wall heating. In 1960, there was made the floor heating system as using hot water boiler used wood shaving as a fuel, this heating system used in nowadays (Figure 3.8) [36].

The heating system was used in Alibey bath as in the original baths of the Ottoman Empire in Anatolia. As in many other historical baths in Anatolia, the order and organization of spaces in the Alibey bath were directly affected by the development of the heating systems. The main units of the heating system in the Alibey bath was the firewood storage room, furnace, copper boiler, hot water tank, hypocaust and chimneys.

In this bath, the wood or timber was burnt in the furnace, which was located under the hot water tank resulting with the water was heated by fire. Flue gas caused by this process of burning up of wood or timber circulates inside the hypocaust. Therefore the interior spaces of the bath were heated. Location of the chimney comes from the traditional heating system can be seen in Figure 3.9 as the front of the photograph and the chimney used nowadays for floor heating system can be seen at the backside of the photograph.

Figure 3.8. Hot Water Boiler.

Figure 3.9. The Chimney.

After circulating in the hypocaust, the exhaust gases coming from the furnace were taken out under the floor in the hypocaust via draft chimneys with switching dampers [37], which regulate the flue gas pressure. Only two chimneys from the past can be seen from the street (Figures 3.10 and 11).

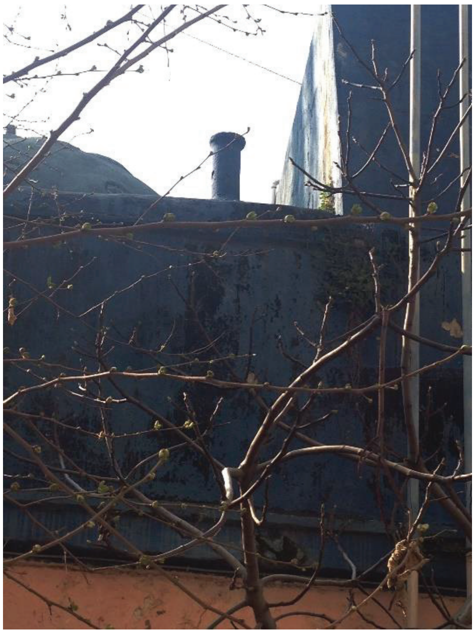


Figure 3.10. The Chimney.

Figure 3.11 The Chimney.

CHAPTER 4

METHODOLOGY

In this chapter, the Alibey bath geometry is occupied and the hypocaust system plan scheme of Alibey bath is foreseen. Then, a grid generation is prepared through "ANSYS Meshing" tool. Secondly, the boundary conditions are defined for building elements individually. So, heated rooms of the bath were modeled and analyzed by the original heating system with different chimney configurations and the modern under floor heating system.

This research based on the "heated rooms of the Alibey bath" which are four adjacent rooms in order to survey the thermal conditions. 3D geometry is made of the selected environmental conditions, the definition of the thermo-physical properties of boundary materials and the characterization of the Alibey bath plan scheme for fluid dynamics simulation environment. The simulation program predict useful data for temperature distribution, airflow patterns at the different sections of the bath and heat transfer rates from hypocaust system to the heated bath sections in the Alibey bath. Through computational fluid dynamics (CFD), Alibey bath on 3D model is replicated and the examined heat transfer rate on the hypocaust system of the bath where hot gas is circulating before exiting through the chimneys.

All considering above, the questions are answered:

a) the temperature distribution of hot gas through the hypocaust system,
b) what can the chimney configuration be necessary for homogenous temperature distribution at the floor surface of the heated rooms,
c) the flow patterns in the hypocaust system for the different chimney configuration owing to checking the chimney is working or not,
d) the floor heating system which used hot water flowed in the pipes, is also analyzed for today's usage and compared to the traditional hypocaust system,
e) heat transfer rates are obtained for different usages and thermal efficiencies are also calculated.

In order to investigate the situations mentioned above, preliminary data and parameters are gathered about the Alibey bath and 2D plans are developed to understand plan scheme and chimneys location before 3D models.

4.1. Geometry

In this study, the bath has two hot rooms with dimensions of 5.80 m x 5.45 m (H1) and 5.45 m x 2.50 m (H2) and two warm rooms with dimensions of 1.85 m x 5.80 m (W1) and 5.80 m x 2.80 m (W2) shown in Figure 4.1. All places are approved same height in the Alibey bath as 5.00 m which are not included in the dome height (it is height of the wall). In addition, gate gaps which are connected the hot and warm rooms are defined as 0.80 m width and 2.20 m height. These places are measured in the Alibey bath, before the 3D model is occupied in ANSYS Fluent and only places where the heating system is located in the bath are modeled [38].

In 3D geometry, the thickness of walls is defined as 0.80 m without windows and thickness of roof is defined as 0.60 m as an average values. The domes are assumed to be semi-spherical and the inner radius is defined as 2.80 m (H1), 1.35 m (H2), 1.06 m (W1) and 1.06 m (W2) for each room individually [3].The flue gas chimneys are made of brick material and square shape with 0.36 m and the total height of chimneys are defined as 5.80 m. The chimneys are raised over the roof as 0.80 m [23].

It is not possible to see the traces of the old heating system since the floor heating system was made over the hypocaust system in the Alibey bath. Thus, the hypocaust system was predicted in the Alibey bath based on the previous researches about the hypocaust systems of the Roman and Turkish baths. In addition, *pilaes* (support elements for the floor) are designed as the total height of 1.10 m in the hypocaust and they are made of brick and khorasan mortar which are overlapped. Every brick has 0.06 m height, 0.35 m length and these bricks are joined with khorasan (brickdust) mortar each other. Their gaps between *pilaes* are assumed to be 0.75 m, 0.80 m and 0.90 m at the different section of the bath depends on the geometry seen in Figure 4.1. [14, 19, 27 and 29].

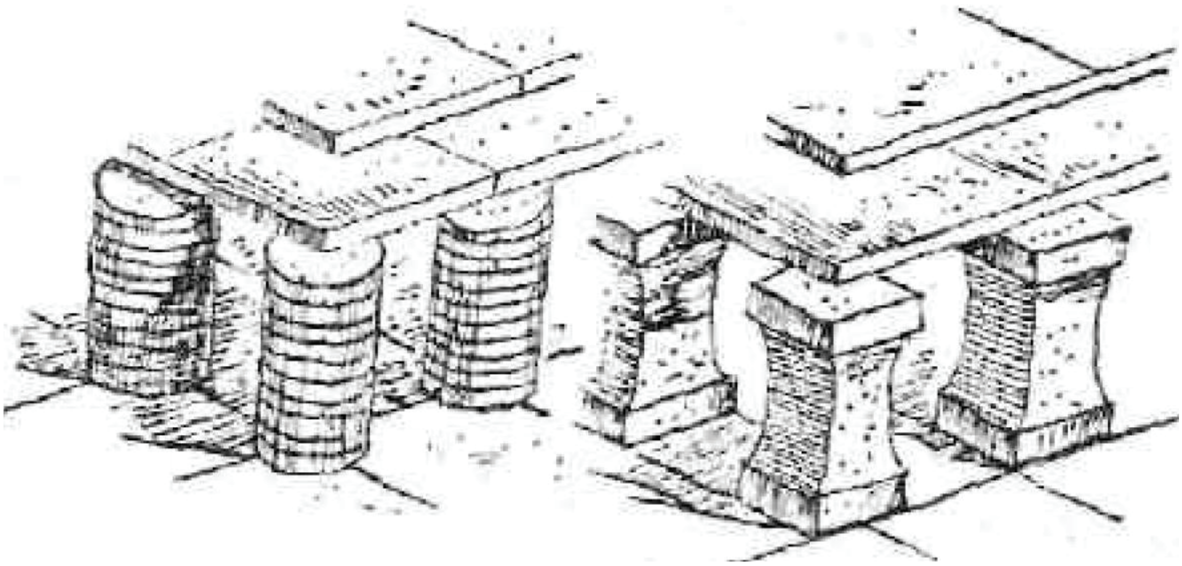


Figure 4.1. Drawings showing the construction of the hypocaust (raised floor) of historical baths [20].

According to the assumptions described above, one of the hot bath's hypocaust is made of 42 rectangle support elements which are located along the main hot bath called H1 in Figure 4.2. Hot bath (H1)'s hypocaust system consists of 7 *pilae* lines and every line has 6 *pilaes* and their gaps are approximately 0.90 m. The other heated room (H2) comprises of 4 *pilae* lines and every line has 6 *pilaes* and their gaps are (approximately 0.75 m.) the same other hot room numbered H1. One of the warm rooms, W1, has 1.85 m x 5.80 m dimensions which consists of 7 *pilae* lines and every line has 3 *pilaes* and their gaps between *pilaes* are 0.75 m. Another warm room (W2)'s *pilae* lines are 7 and each line has 4 *pilaes*, their gaps between *pilaes* are 0.80 m (Figures 4.2 and 4.3.).These *pilaes* carry the bath's floor which thickness is 0.30 m and made of brick, khorasan mortar and the marble at the top.

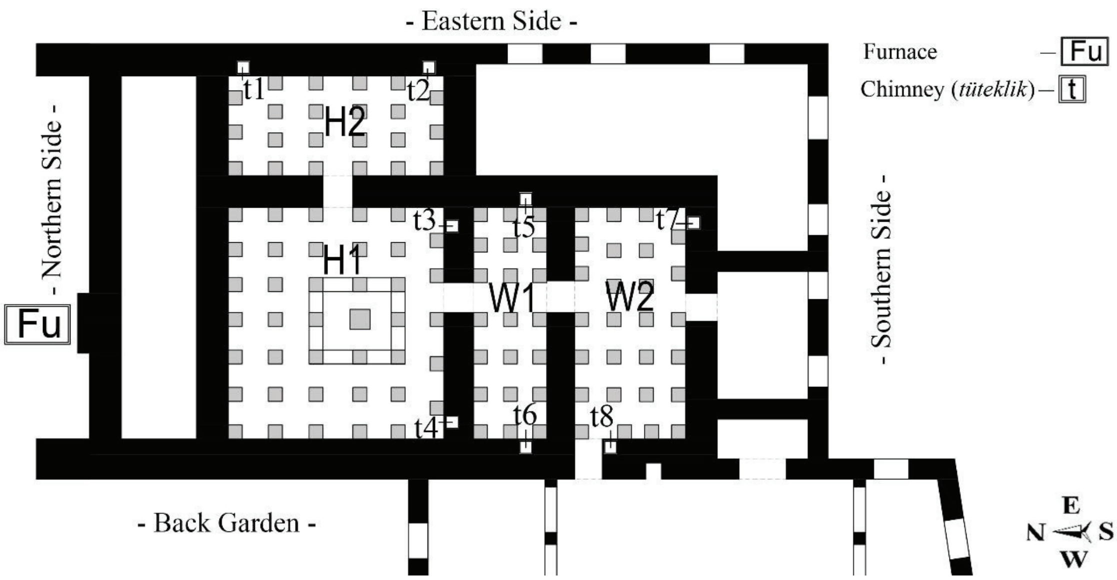


Figure 4.2. The hypocaust system of the Alibey Bath.

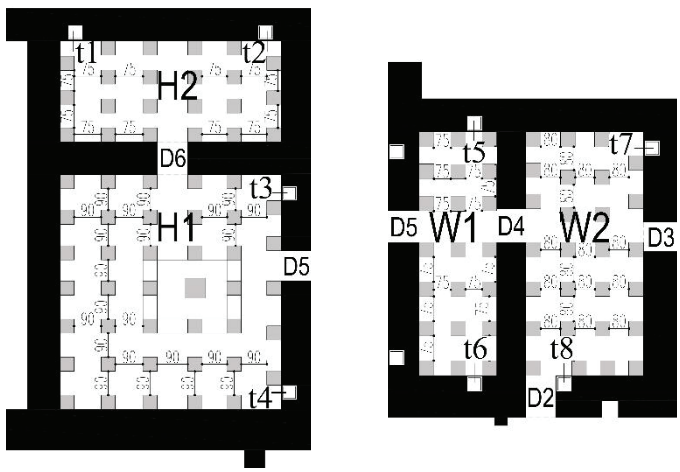


Figure 4.3. The details of the hypocaust system in Alibey Bath.

4.2. CFD Simulations

ANSYS Fluent software which is used in this thesis is a numerical environment to simulate the fluid flow and heat transfer by Computational Fluid Dynamics (CFD) tools. The governing equations (continuity, momentum and energy) are solved by using the finite-volume method. The fluid is Newtonian and incompressible. If the flow is steady, fully turbulent and three dimensional, additional equations are applied under different model applications. In this current numerical problem, Reynolds Averaged

Navier Stokes (RANS) flow separation model with k-ε transport equations is applied. For improving the standard k-ε model performance, the realizable k-ε model is used in the analysis [38].

These analyses are based on a steady-state condition for all situations. Because of that, thermal conductivities for all building elements are defined in the CFD code. Each building element is erected for different materials described each thermal resistance value for calculating average thermal conductivities for each building element individually. The thermal conductivities values of building materials were assumed to be constant and homogenous. The thermo-physical properties of the air were assumed to be constant except for density. Viscous dissipation and radiation effects were neglected.

Geometry has created an integration of CAD and 3D survey software and it is transferred into the "ANSYS Design Modeler". 3D model is a gateway for analysis with software from ANSYS Fluent. Then, a grid of generation is prepared through "ANSYS Meshing". The mesh generation process is a tool of ANSYS Fluent for the purpose of a study grid of calculus and accurate simulation solutions.

Considering the complex geometry of the bath's air volume and building elements, the mess is consisted of polyhedral elements, to obtain suitable calculations and representation bath's conditions. Moreover, the 3D grid is constituted by a total of 1,783,144 cells. There is no cell above %80 skewness, all cells close to ideal shape. Additionally, the mesh is developed as "coarse" to "fine" quality. The grids of the simulation model have used the function as "body sizing" and the maximum and minimum cell sizes are 0.10 m and 0.01 m, respectively (Figure 4.4).

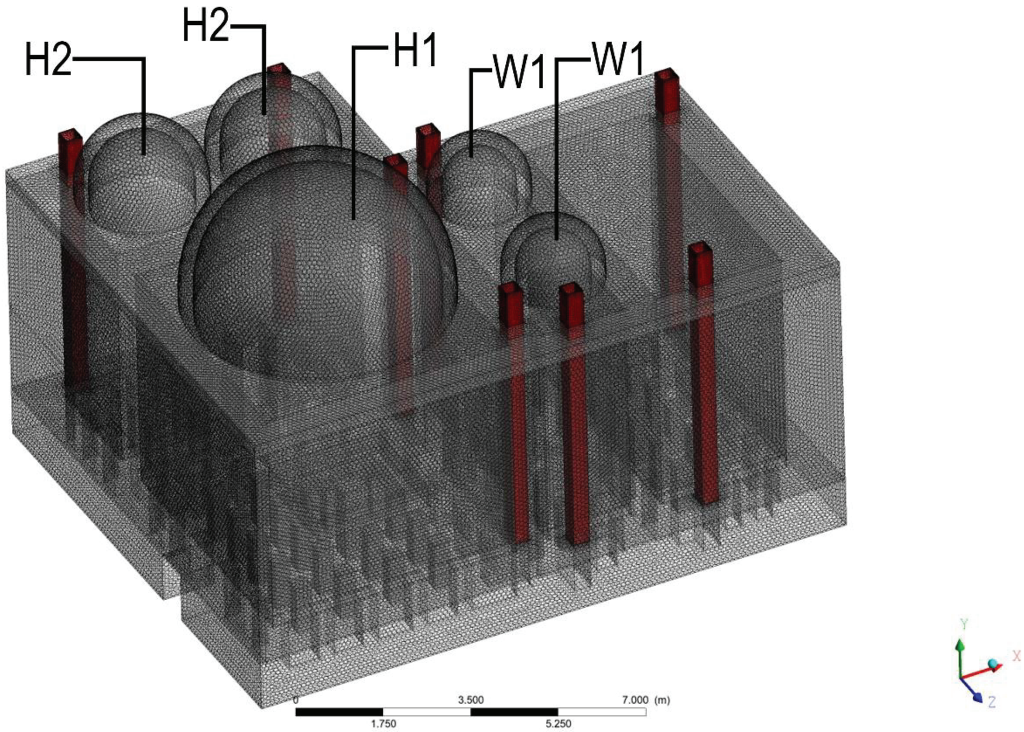


Figure 4.4. Polyhedral mesh structure of the bath.

4.3. Boundary Conditions

In this simulation, key zones are defined for analysis which are the external wall, internal wall, heated wall, heated floor, roof, a wall of water storage. The conditions are summarized below:

- The convective heat transfer coefficient of the external walls is defined as 25 W/m²K [39]. Average outside temperature is considered as 8.8°C which represents to the average January temperature (as the coldest month) for İzmir last 10 years [40].
- The internal wall which is adjacent to the service area and changing room is defined as 20°C and the convective heat transfer coefficient of the internal walls is defined as 7.69 W/m²K [39].
- 2 m of 5 m wall which is adjacent hot water tank (Figure 4.2) is predicted 2 m of 5 m with water and this wall temperature is defined as 50°C and the convective heat transfer coefficient of the wall is considered 100 W/m²K as an assumption. The upper part of the tank, 3 m of 5 m wall, interacts with air which is assumed

to be 20°C and the convective heat transfer coefficient of internal wall is also assumed to be 7.69 W/m²K (Figure 4.5 and Table 4.1).

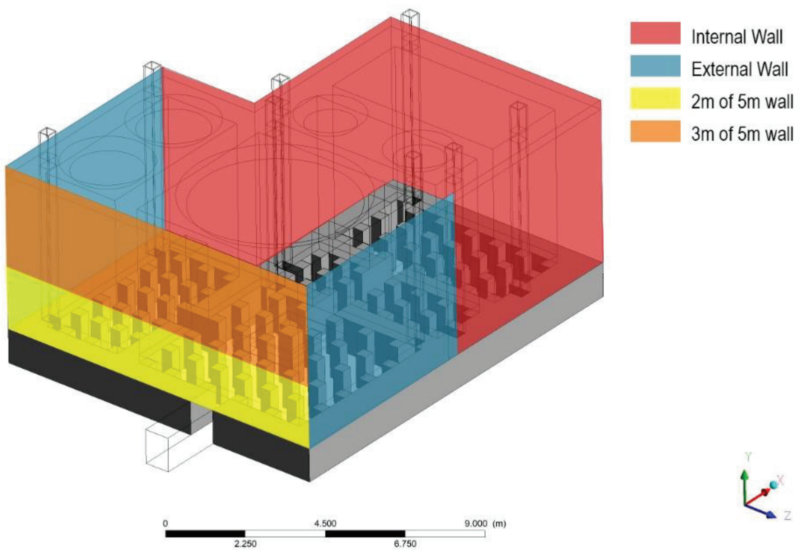


Figure 4.5. Perspective of the hypocaust system and walls of the Alibey Bath.

Table 4.1. Convective heat transfer coefficients and the related environment temperatures

	Convective heat transfer cof. (W/m²K)	Temperature (°C)
External Wall	25	8.8
Internal Wall	7.69	20
2m of 5 m wall in hot water tank	100	50
3m of 5 m wall in hot water tank	7.69	20

- Average thermal conductivity values of the external and internal walls are calculated as 1.31 W/m°C. In addition, the thermal conductivity of floor is defined as 1.81 W/m°C and the thermal conductivity of the roof is determined as 1.28 W/m°C (Figure 4.5). The material's thermal conductivity values are defined individually by using the reference numbered 41 (Table 4.2-3). Average thermal conductivity values (k_{avg}) are calculated by using Equation 4.1:

$$\frac{L_{total}}{k_{avg}} = \sum_{i=1}^{N} \frac{L_i}{k_i} \quad (4.1)$$

Table 4.2. Building materials thermal conductivity values and their dimensions [42].

Material	Finishing Coat	Scratching Coat	Brick	Marble
Thermal Conductivity	0.7 W/m°C	1.4 W/m°C	1.3 W/m°C	3.5 W/m°C
Roof	0.02 m - 0.03 m	0.02 m - 0.03 m	0.50 m	0.03 m
Floor	0.02 m - 0.03 m	0.02 m - 0.03 m	0.20 m	-
External/Internal Wall	0.02 m - 0.03 m	0.02 m - 0.03 m	0.80 m	0.03 m

Table 4.3. Values of average thermal conductivity

Average Thermal Conductivity Values	
External - Internal Wall	1.31 W/m°C
Floor	1.81 W/m°C
Roof	1.28 W/m°C

- Inlet flue gas temperature to the hypocaust system is a determining factor as a boundary condition. This temperature is a time depended value considering the fuel consumption in the furnace. Hüser [24] showed the transient temperature measurements which is changing by time during the experiment depends on consuming of fuel [24]. Kretzschmer [13] draw the temperature distribution through the furnace and the temperature values changed significantly depends on the distance from the fire. Inlet flue gas temperature is the main driving effect to obtain the thermal analysis of the previous CFD studies [29, 30 and 31]. In the light of these information, inlet flue gas temperature to the hypocaust system is assumed as 90°C.
- Thermo-physical properties of the flue gas in the hypocaust system and air in the heated rooms are defined by using average temperature. But, the density of the both environment is based on the temperature variation.
- Inlet flue gas average velocity to the hypocaust system is also another significant factor to investigate the thermal behavior of the bath. This value is calculated by using fuel consumption with air-fuel ratio and the amount of fuel mainly

depends on outside climatic conditions. Fuel consumption is also time depended value and it changes with conditions like outside temperature and occupant usage. So, there are different inlet conditions in the references [29, 30 and 31] for the different bath buildings. In the current study, under steady-state condition, uniform velocity magnitude is defined as 0.2 m/s.

- Chimney outlet condition is defined as "pressure outlet" in all CFD analyses

The 3D simulation study is conducted by considering all outdoor conditions, wall, floor and roof structures in order to provide thermal behavior of the bath. Different scenarios are hypothesized about chimney configurations as shown in Figures 4.6-4.9. Exact locations of the chimneys are not clear in the bath nowadays and there is no record in the literature about this. Only two chimney positions are defined clearly in the Alibey bath as shown in Figures 3.10 and 3.11. But, the number of chimneys must be increased for working of the bath. Thus, some simulations are improved in order to investigate the thermal condition of the bath (Figures 4.6-4.9).

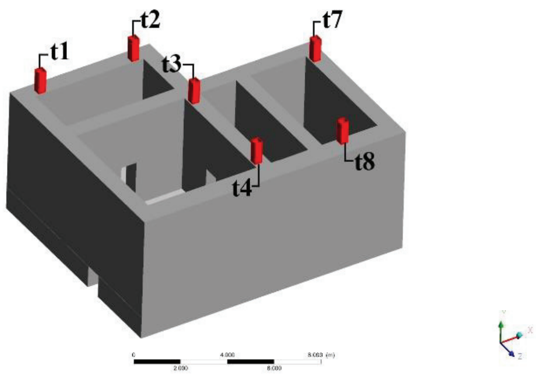


Figure 4.6. Scenario a.

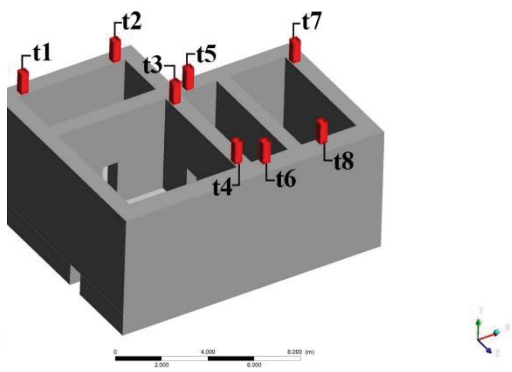


Figure 4.7. Scenario b.

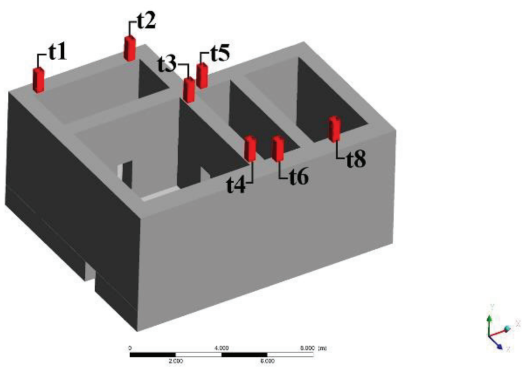


Figure 4.8. Scenario c.

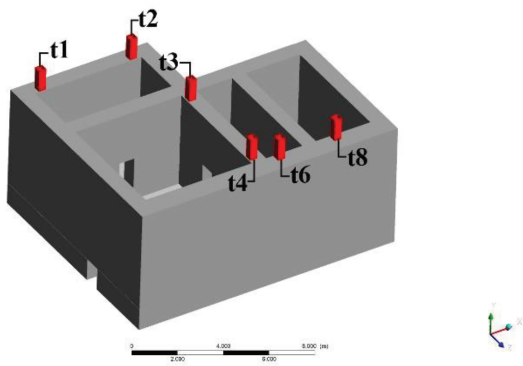


Figure 4.9. Scenario d.

In Scenario a, two chimneys (t1 and t2) are seen on the hot bath from past but they are not enough for heating up the bath. The locations of new chimneys are assumed at some places to provide heating to the Alibey bath. Two chimneys (t3 and t4) are allocated in the big hot bath. In addition to this, two more chimneys (t7 and t8) are placed in the warm bath (Figures 4.6). The flue gas energy from the furnace should reach every place of the Alibey bath.

Secondly, in Scenario b, the same position of the chimneys are used for the same scenario a in the 3D model but it was recognized the flue gas in the hypocaust do not reach some places such as another warm bath. Thus, two more chimneys (t5 and t6) are added to provide distribution of the flue gas within the hypocaust system (Figures 4.7).

Thirdly, in Scenario c, same positions of the chimneys are used as scenario b and canceled one chimney (t7) from warm bath because of the fact that most of the flue gas exhaust from the furnace go through directly to the warm bath (Figures 4.8).

Fourthly, in Scenario d, same position of the chimneys are used as scenario c and one more chimney (t5) is cancelled from the warm bath (Figures 4.9).

At the end, as a fifth scenario, 3D simulation of heating system used today is also designed for the purpose of comparing between the heating system of the Alibey bath from past to present. So, the floor heating system is used for heating of the Alibey bath nowadays. In this system, hot water circulation is provided through the pipes laid from the floor to heat up the hot and warm rooms. The distance between the hot water pipes laid inside of the floor is different based on desired inside temperature of the bath sections [40].

The same boundary conditions are used for this under floor heating model such as outdoor conditions, average thermal conductivity values and detail of roof, floor and wall sections. Different from the four cases (a, b, c and d) about the heating system with hypocaust previously explained, the significant boundary condition of the system is the heat flux values from the floor heating system used hot water. These values are defined by using trial and error approximation. So, heat flux values are described for considering the average air temperature at the hot rooms and the average air temperature is tried to be close to the human body temperature. This design average air temperature value is obtained by using 60W/m² heat flux value for hot baths. The distance of between pipes is located differently for the floor heating system of the different sections of the Turkish bath. Usually, this distance is used 0.05 m for the hot bath, 0.10 m for the warm bath as shown in Figure 4.10 and 4.11. Pipe configuration is usually not changed for different baths under different indoor environment conditions, but the water temperature is controlled based on the heating load of the individual bath. Average water temperature can be around 55°C. So, the warm baths heat flux value is defined as 30W/m² as a boundary condition.

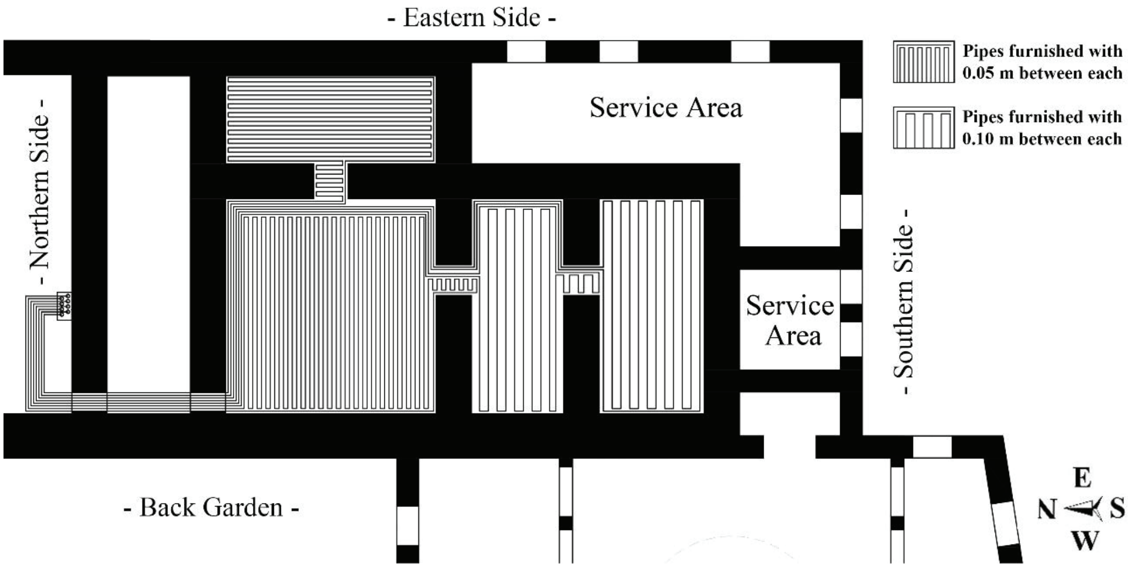


Figure 4.10. Floor heating system of the Alibey Bath [43].

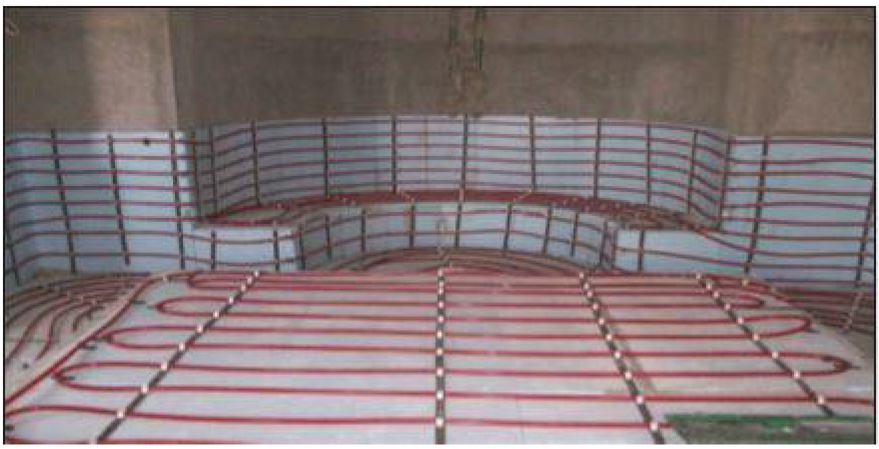


Figure 4.11. Floor heating system [44].

There is also heating from the wall, but not in the Alibey bath in Figure 4.11.

CHAPTER 5

RESULTS

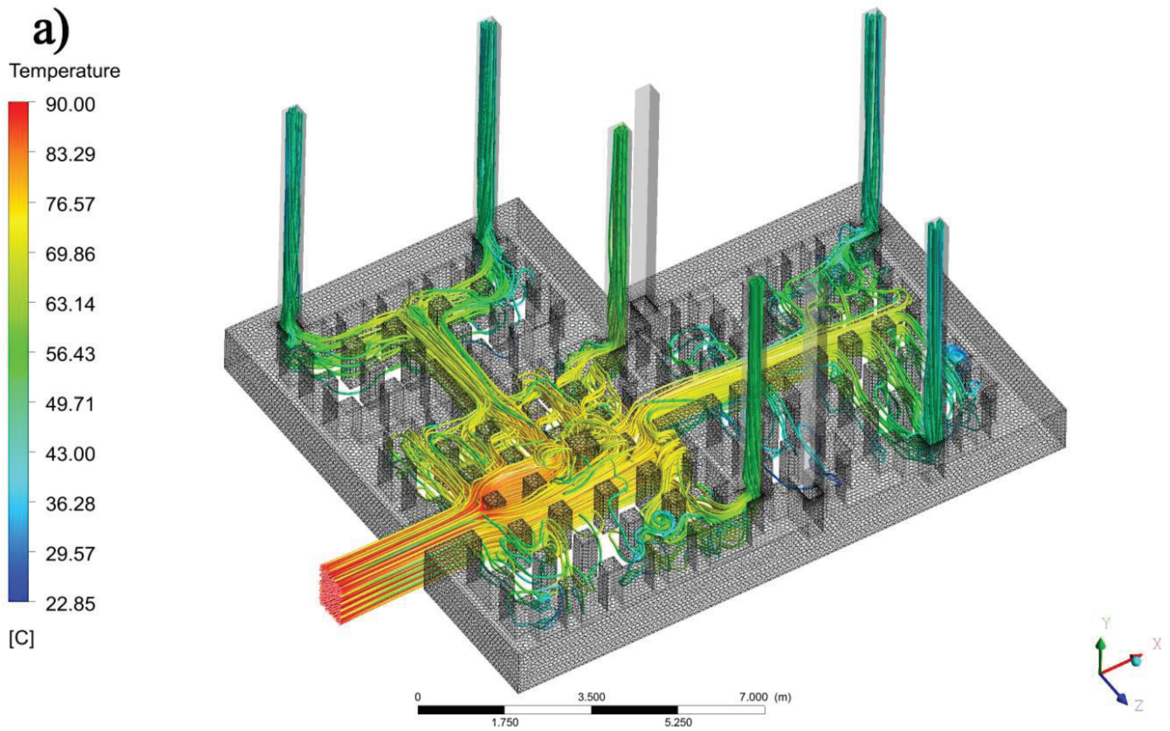
After running the CFD code, simulations results display temperature distributions and velocity fields for five different simulation scenarios of the Alibey bath. Four of them consider traditional heating system which first allows gas to flow throughout the hypocaust system and then exhausts it from the chimneys. The fifth scenario is related to the under floor heating system which commonly used to circulate hot water through the pipes under the floor.

Each scenario shows us different specific results based on given boundary conditions. These scenarios reflect the velocity vector distribution through the hypocaust system for flue gas and inside air flow patterns for the heated rooms. The results also show the temperature distribution in the different section of the spaces and the amount of heat transfer necessary to maintain thermal conditions on the bath.

5.1. The Heating System with Hypocaust

Wood fire in the furnace creates a hot exhaust gas and the gas circulates throughout the hypocaust system, then reach to the atmospheric pressure through the chimneys embedded in the walls. This system is modeled with 3D simulations CFD program to investigate fluid flow and thermal analysis for four different scenarios. When these scenarios are designed, the boundary conditions are kept the same for each scenario, but the location of the chimneys are changed in the 3D simulations.

Fuel gas streamlines start from the furnace and exhaust through the chimneys as shown in Figure 5.1. In Scenarios a, c and d, streamlines do not reach some regions of the hypocaust system of the warm baths obviously because of chimneys positions. But in Scenario b, flue gas reaches almost every regions of the hypocaust system of the bath. Figure 5.1 shows that the flue gas temperature changes through the hypocaust system. The temperature distribution within the streamlines coming from the furnace are also shown in Figure 5.1.



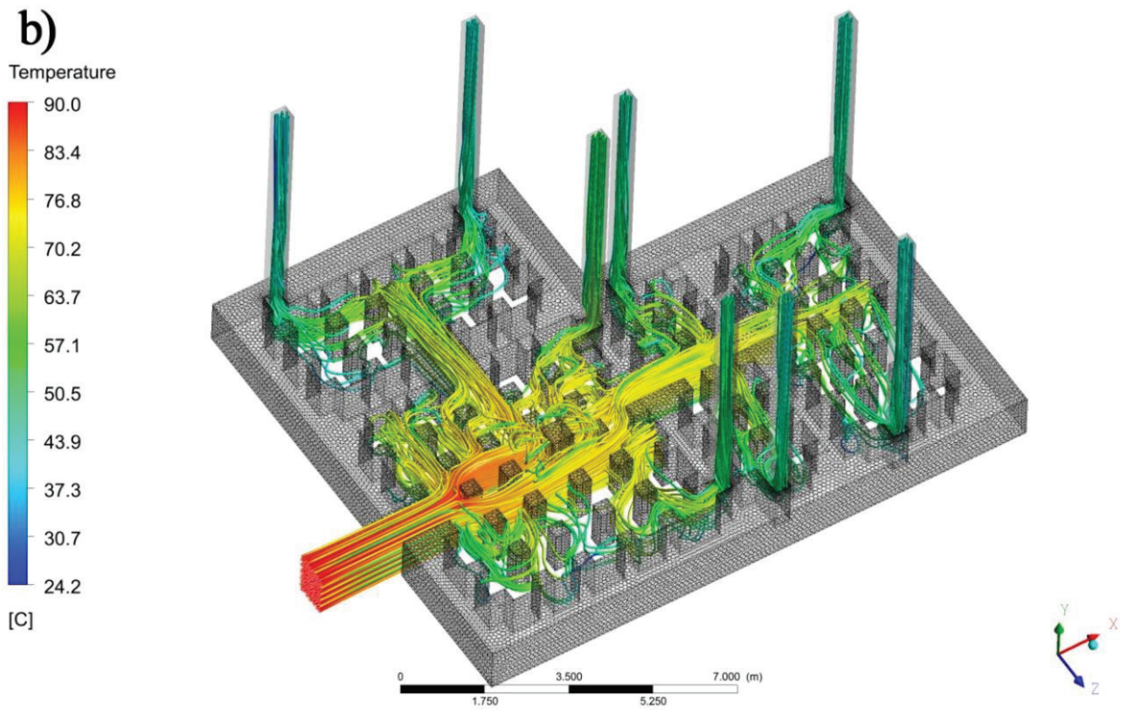


Figure 5.1. Streamlines in the hypocaust for Scenarios a, b, c, and d.

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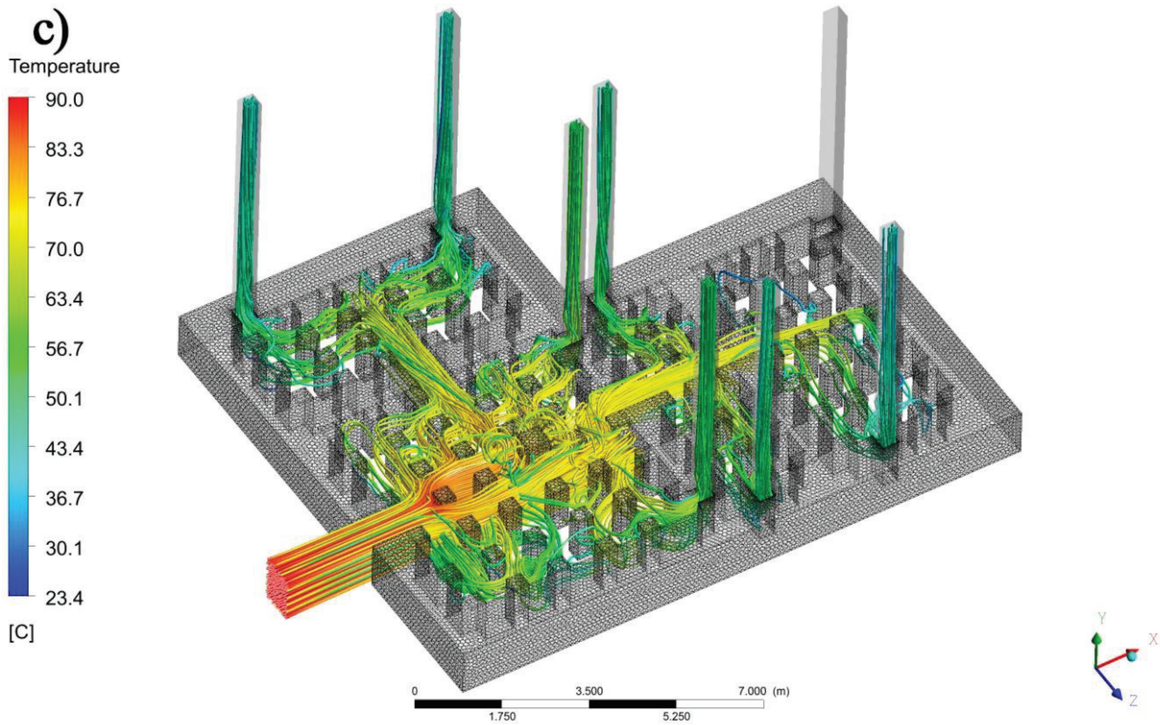

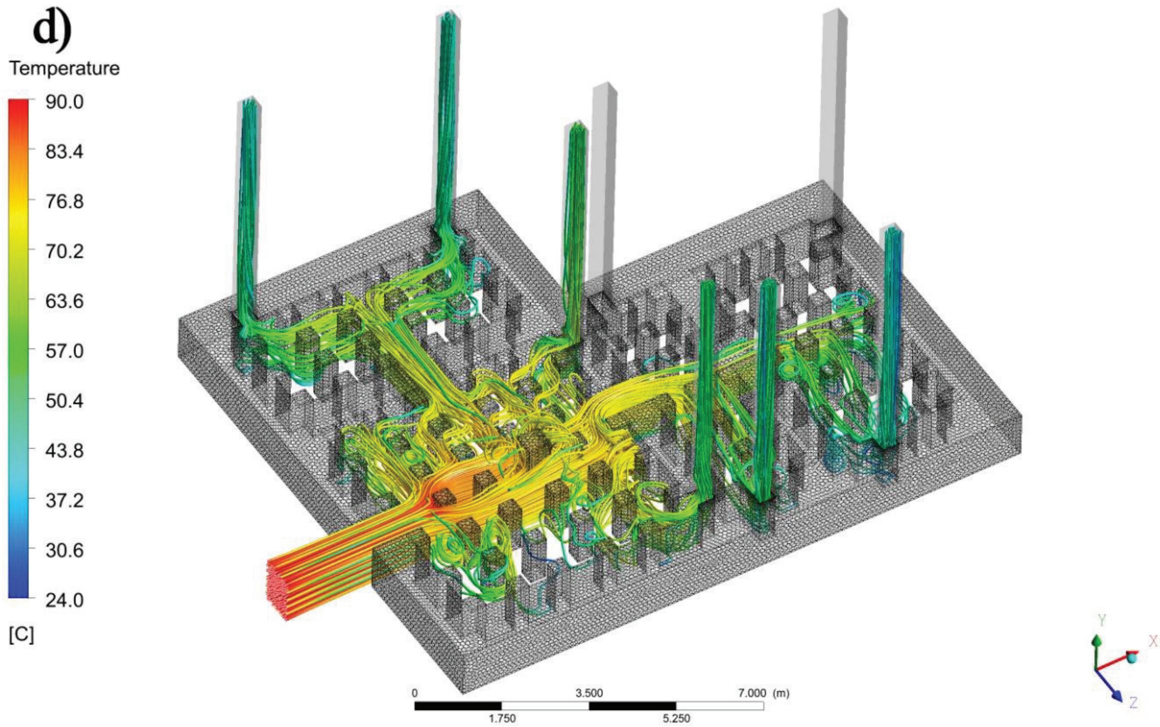

Figure 5.1. (Cont.)

It is assumed that the flue gas exhaust from the furnace with a uniform velocity of 0.2 m/s for four different scenarios namely a, b, c and d. In this process, some of the flue gas flows away from the chimney region and the velocity of flue gas reduces to a value between 0.00 to 0.02 m/s. The flue gas which is directed towards the chimney zones, wants to reach to the atmosphere. Due to this situation, flow separations appear close to the chimney zones for each scenario in the hypocaust and the flue gas velocities increase up to a value between 0.05 and 0.08 m/s. The flue gas distribution is similar for each scenario but the velocity of this gas is different at the same region for each scenario depending on the chimney position. Flue gas velocities increase in the relatively small cross-section areas when the flue gas pass the sections (Figure 5.2).

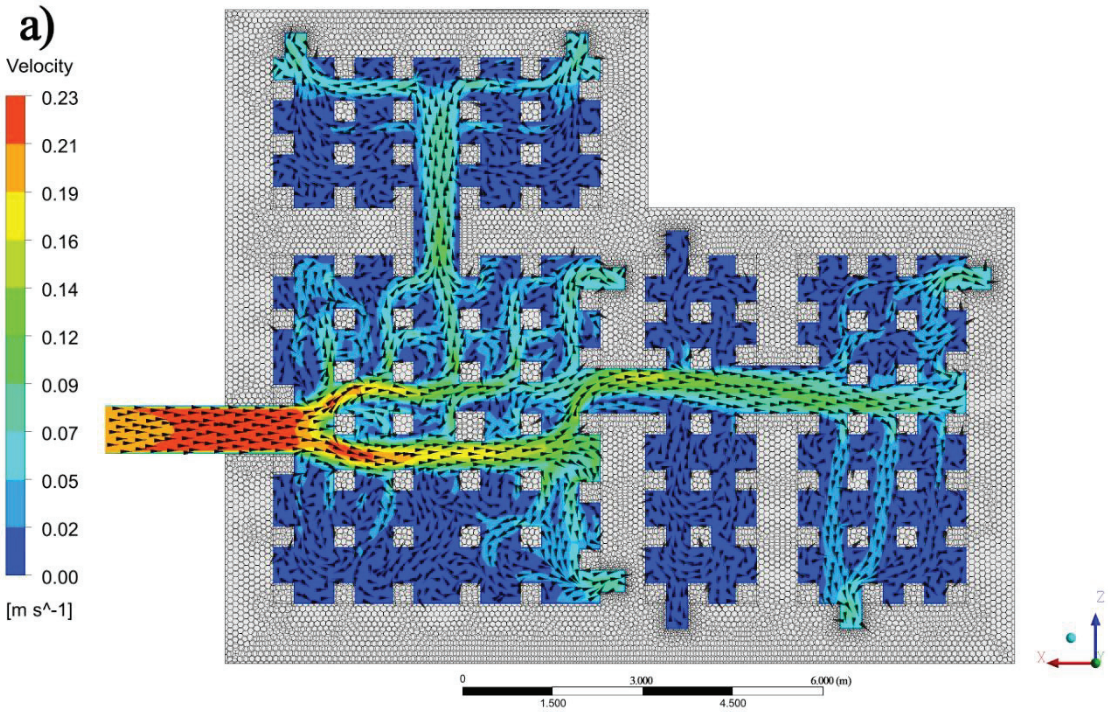

Figure 5.2. The velocity vectors in the hypocaust plan for Scenarios a, b, c and d.

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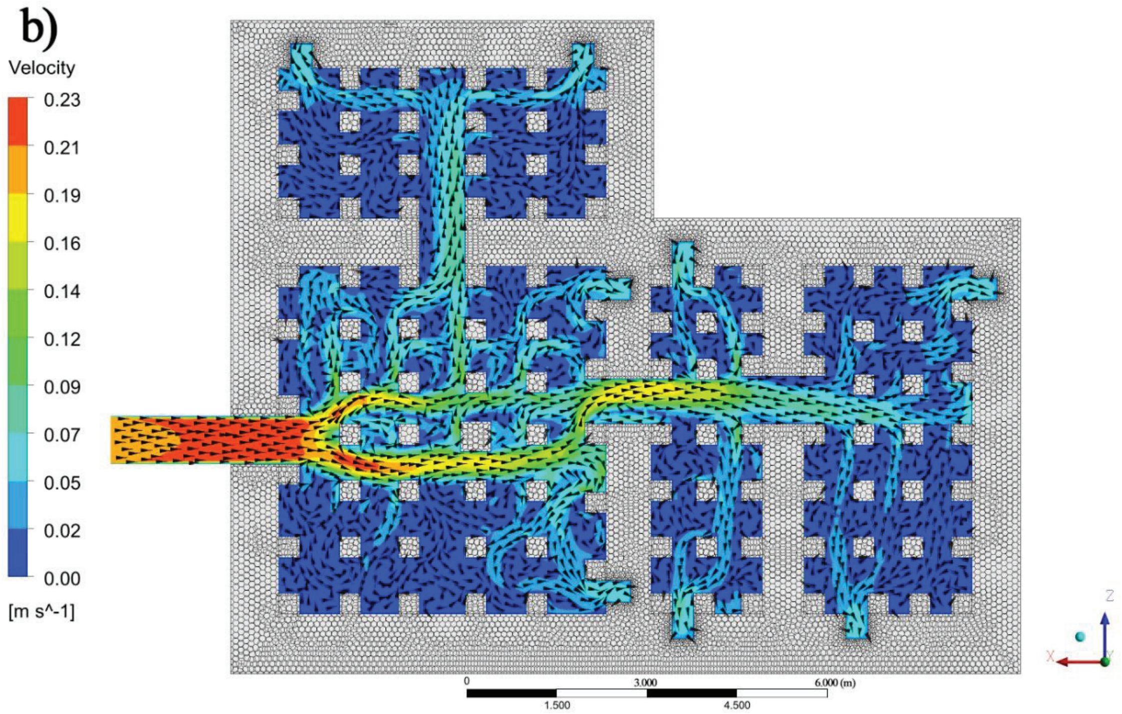

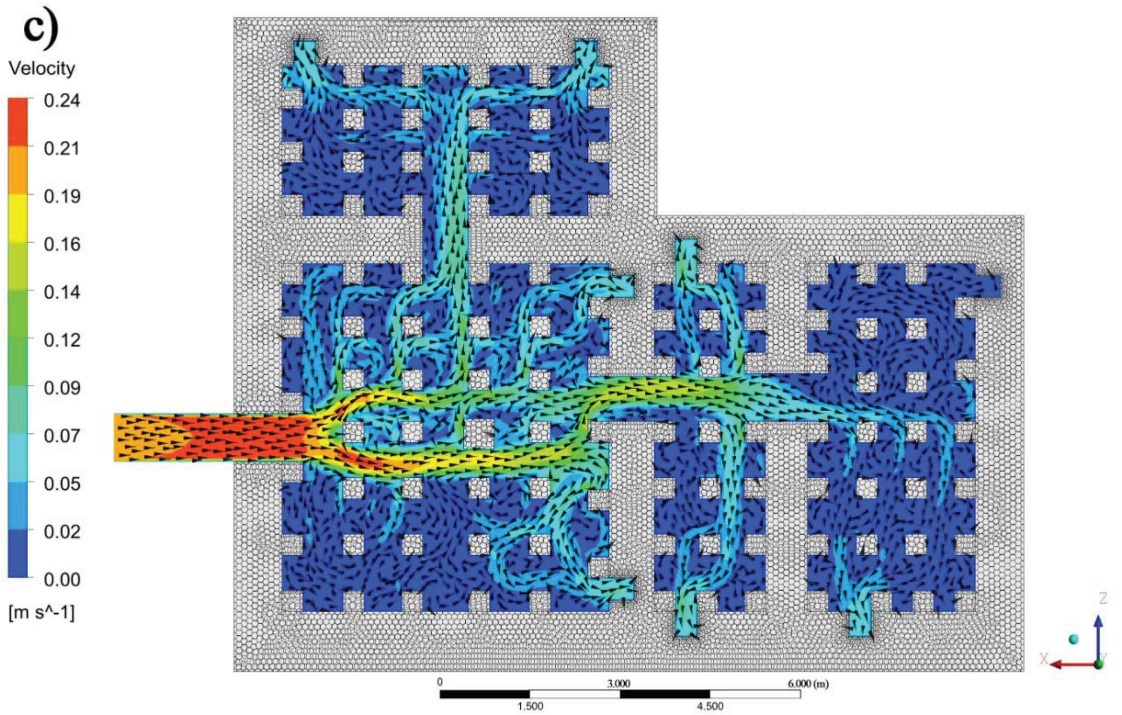

Figure 5.2. (Cont.)

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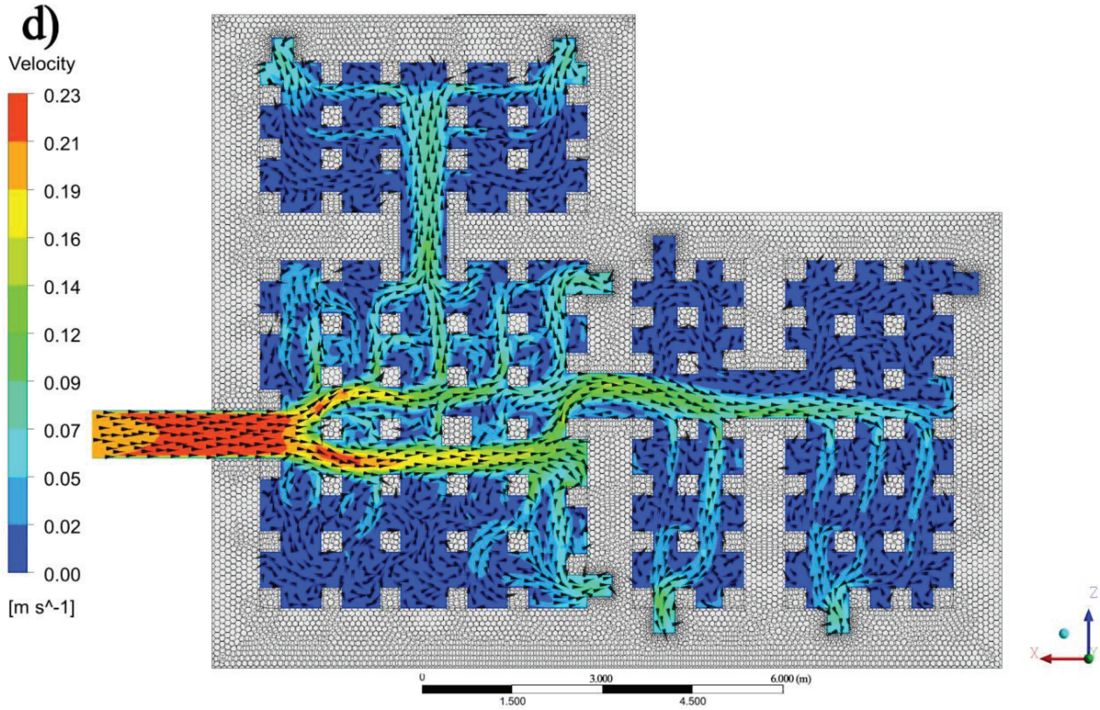
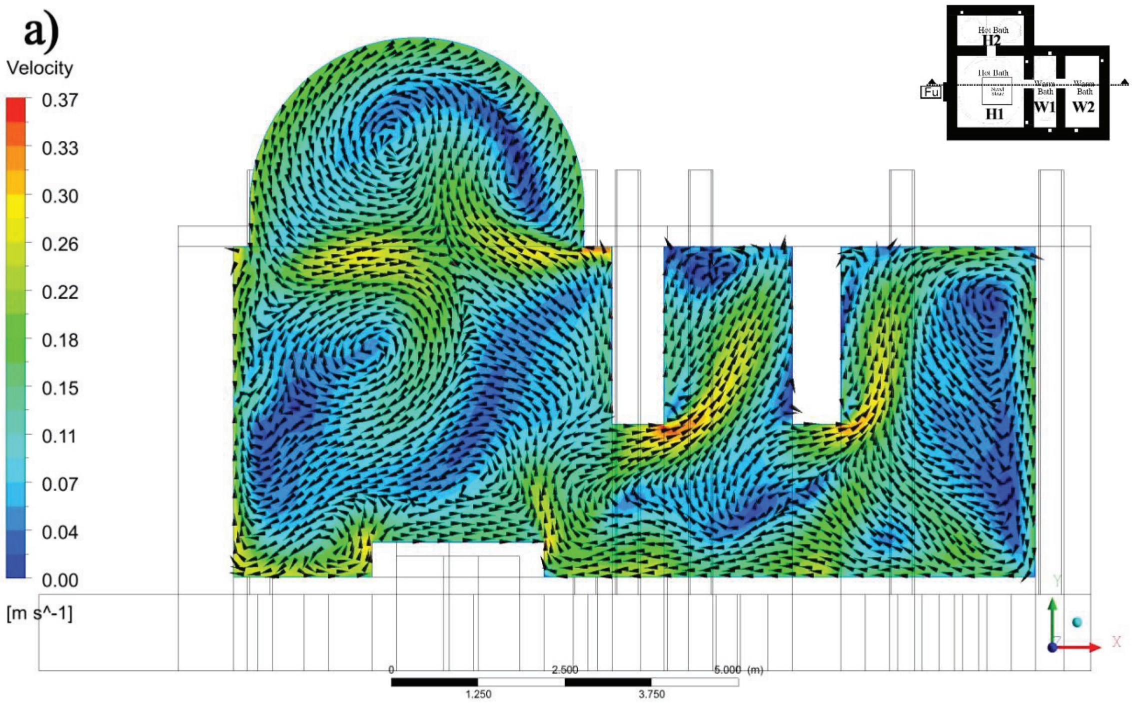


Figure 5.2. (Cont.)

Distribution of the velocity vectors in the heated rooms of the bath has a draw back in the simulation. These phenomena occurring within the bath sections for four scenarios are given in Figure 5.3. The hot air heated from the hypocaust system rises from the floor and try to reach to the dome under the effect of buoyancy forces induced by the density gradients. When the hot air reaches the dome, it begins to cool down and trickles down to the floor. In addition, when the hot air passes from wide volumes to narrow volumes (at the doorways), the velocity of hot air increases relatively. Flow separation appears within these regions. Relatively high values of hot air velocities are observed at the close proximity to the furnace because of hot surfaces which create the air density gradient.



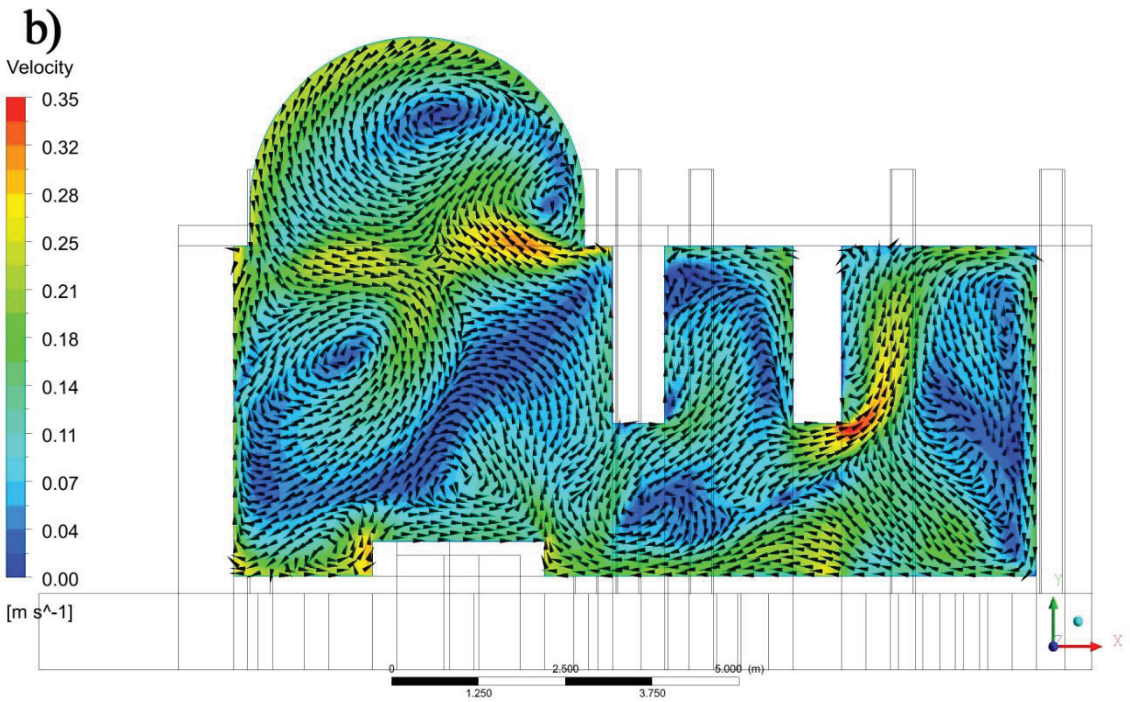


Figure 5.3. The velocity vectors in the x-y-plane for Scenarios a, b, c and d.

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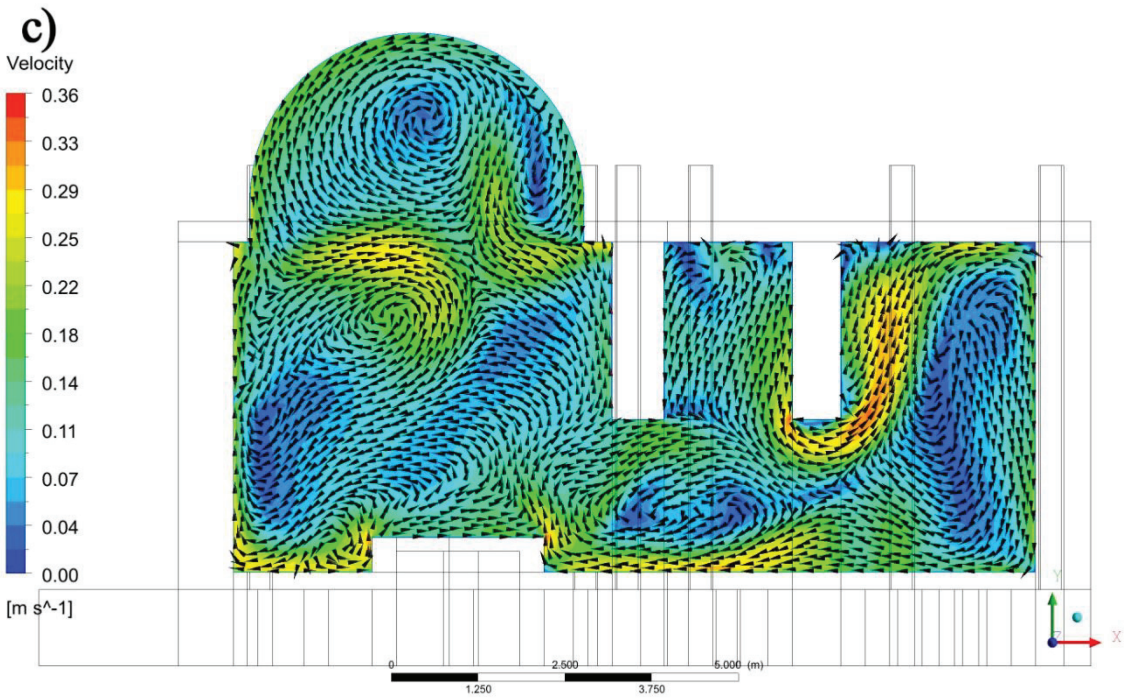

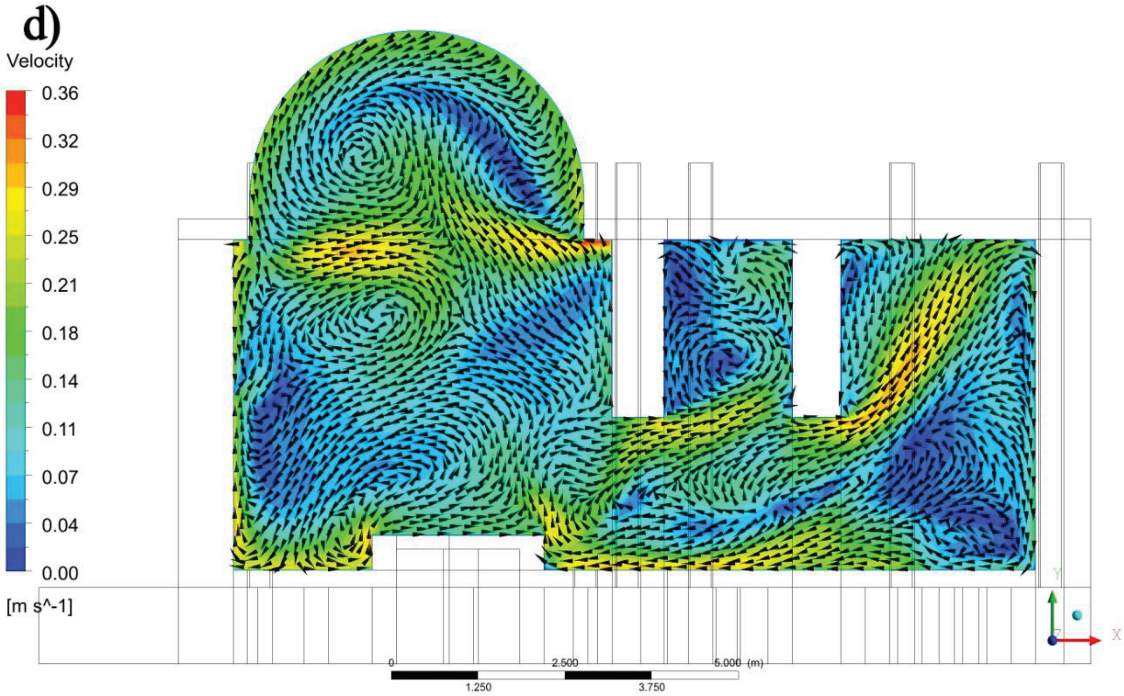

Figure 5.3. (Cont.)

Temperature distributions at the different sections of the bath are shown in Figures 5.4, 5.5 and 5.6. Temperature ranges in the hypocaust system are between 20°C to 90°C. The inlet temperature to the hypocaust from the furnace is assumed to be 90°C uniformly. The temperature decreases around 20°C at some corners of the hypocaust of the warm bath except Scenario b. In Scenario b, the temperature value inside the hypocaust is around 34°C as a minimum value. All of the scenarios show that hot flue gas exhausted from the furnace at a temperature of 90°C and under the navel stone it decreases to a value between 83°C - 76°C. Therefore, most of the thermal energy from the hypocaust transfers to the hot baths and after that flue gas transfers its energy through the warm baths.

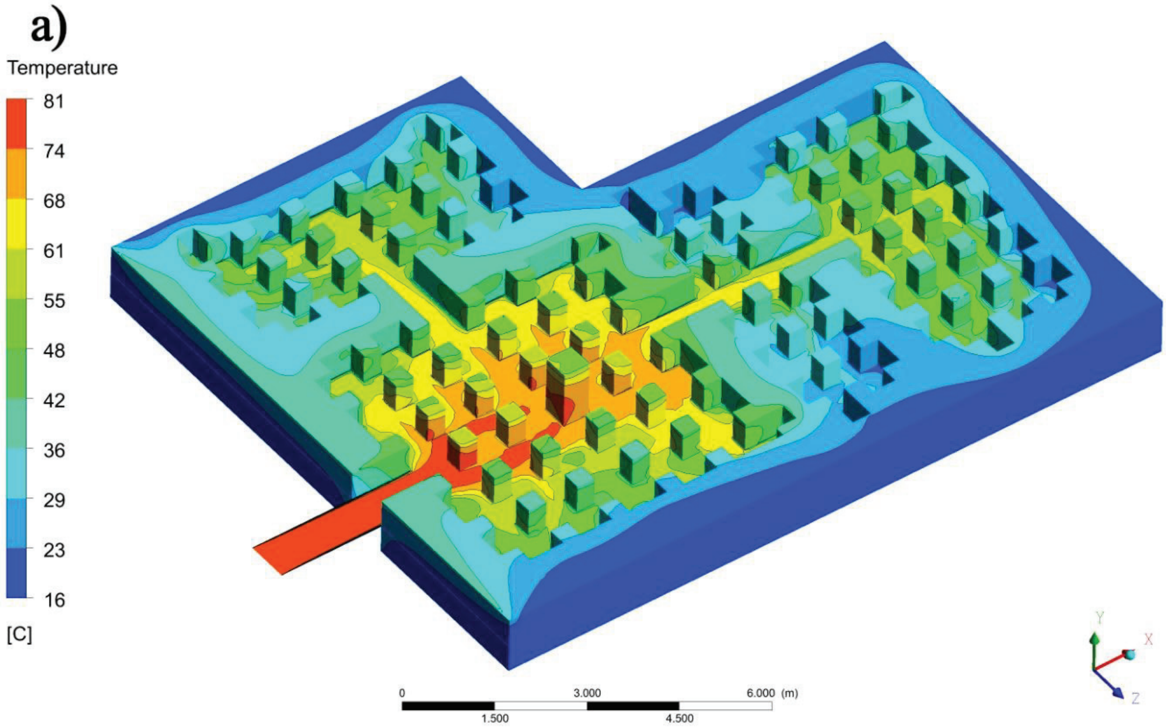

Figure 5.4. The temperature distribution in the hypocaust for Scenarios a, b, c and d.

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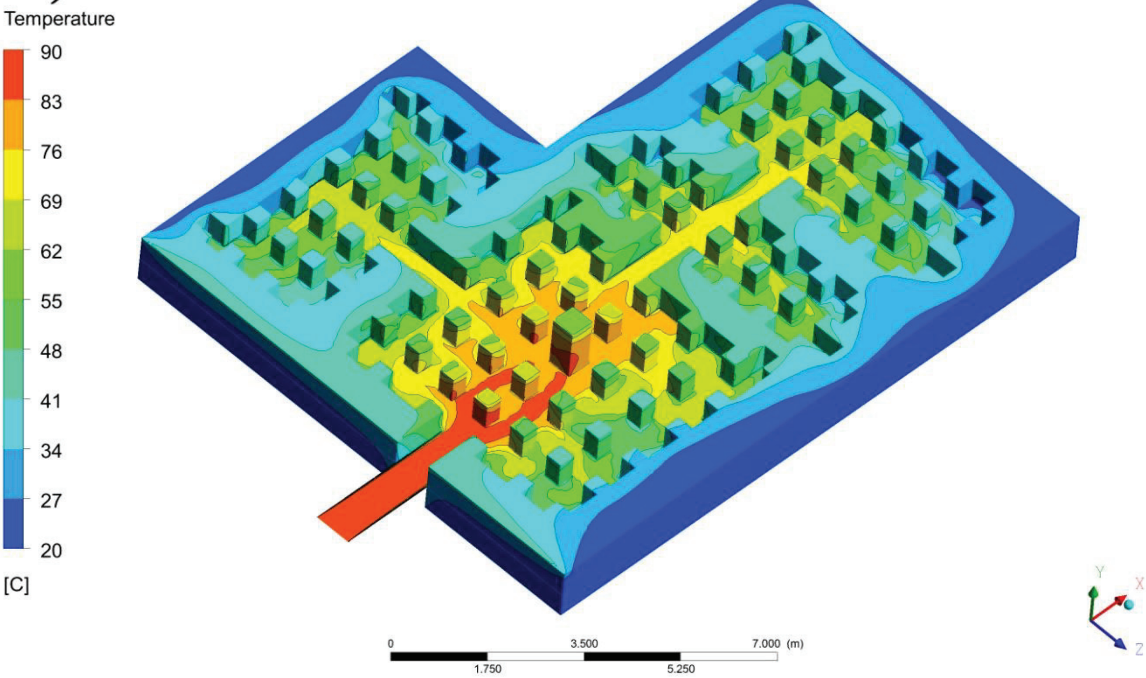
b)



c)

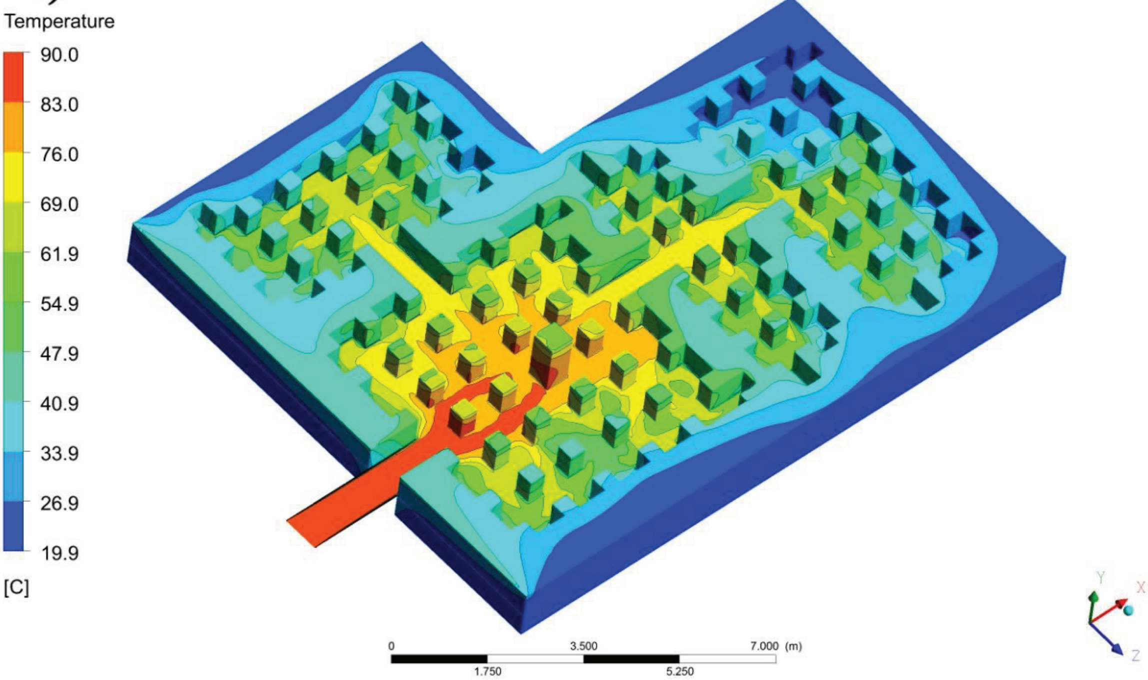


Figure 5.4. (Cont.)

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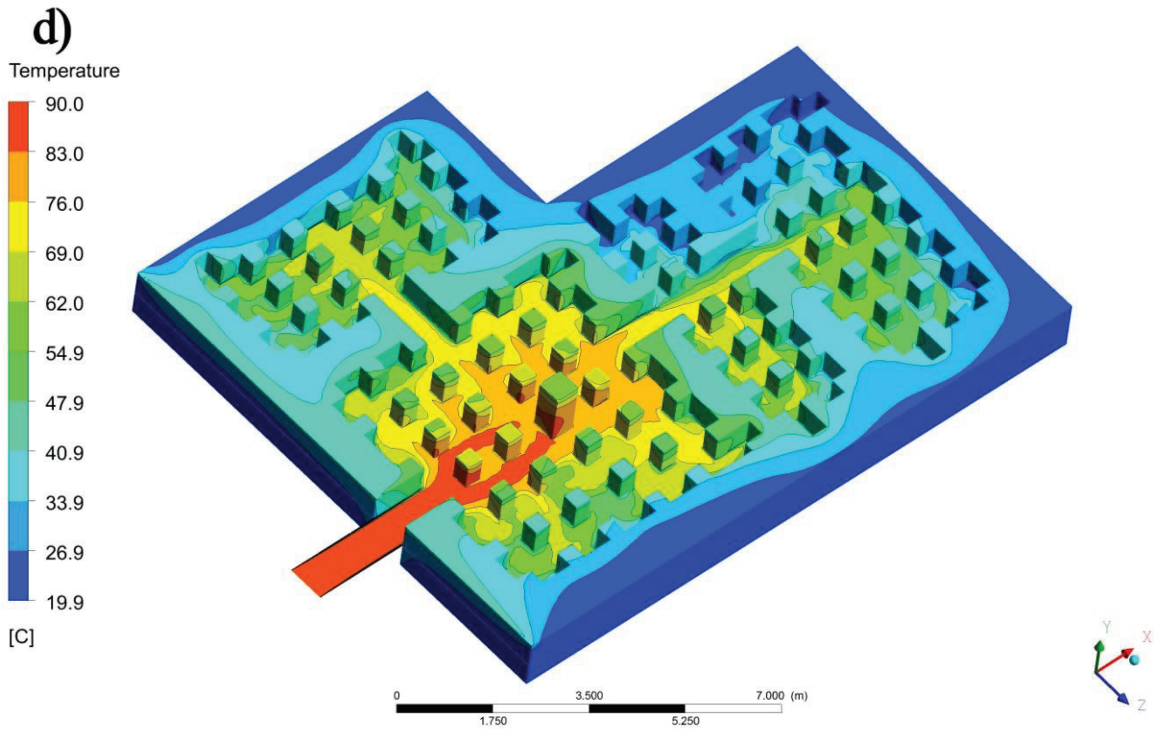

Figure 5.4. (Cont.).

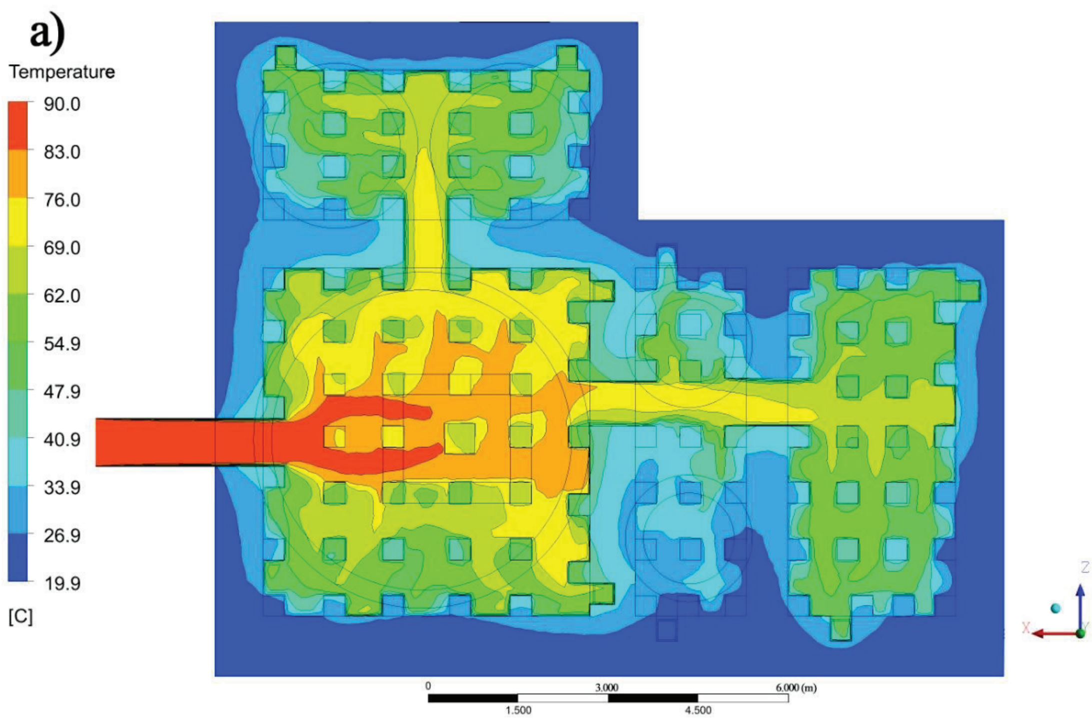

Figure 5.5. The temperature distribution in the hypocaust for Scenarios a, b, c and d.

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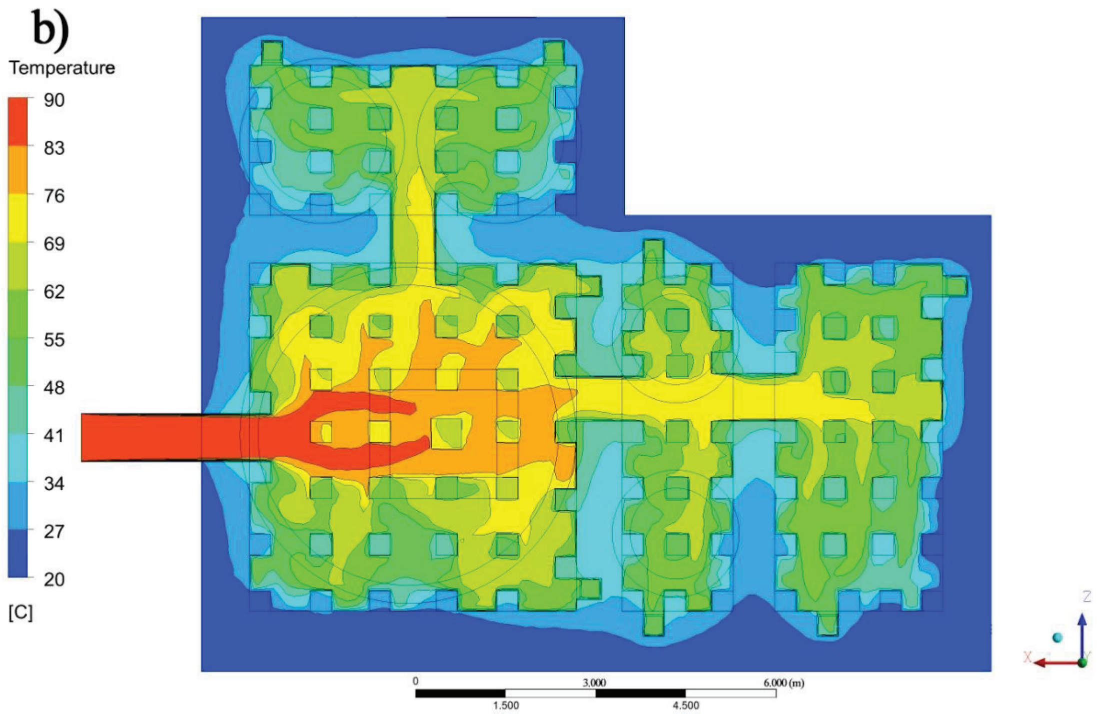

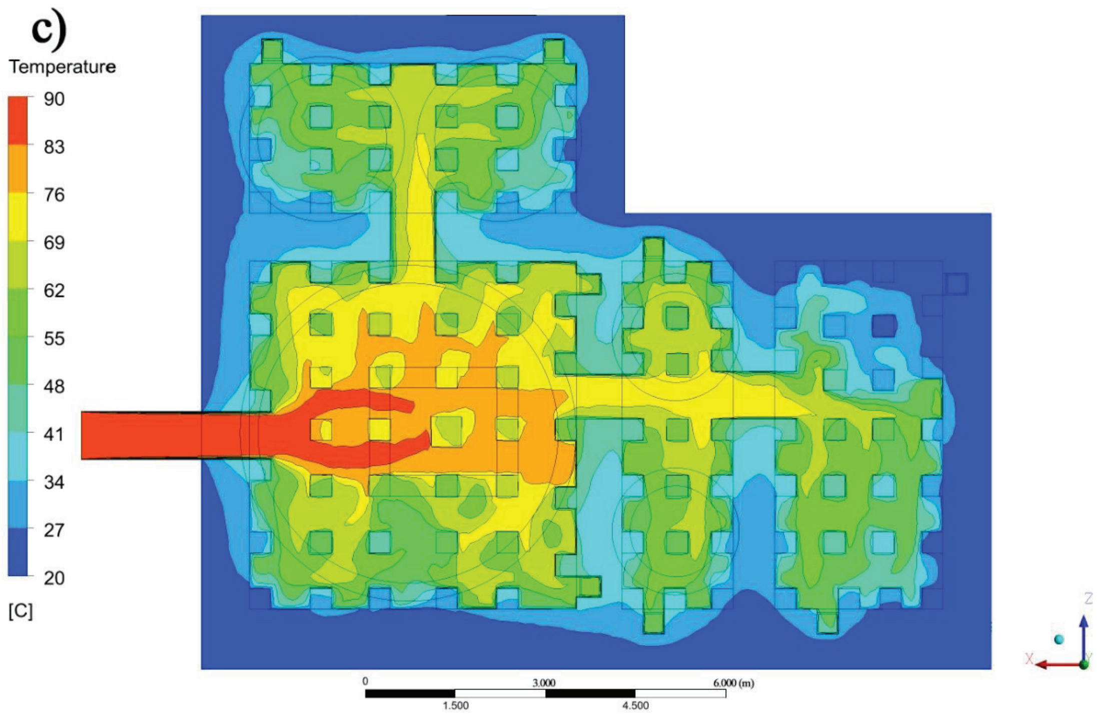

Figure 5.5. (Cont.)

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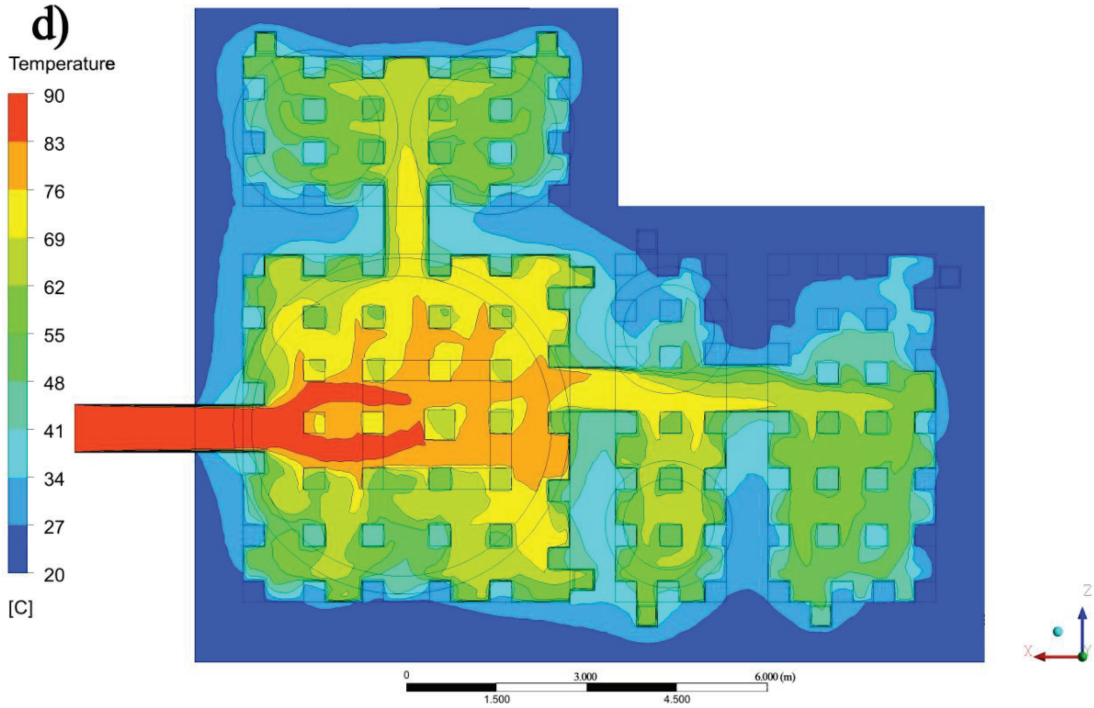
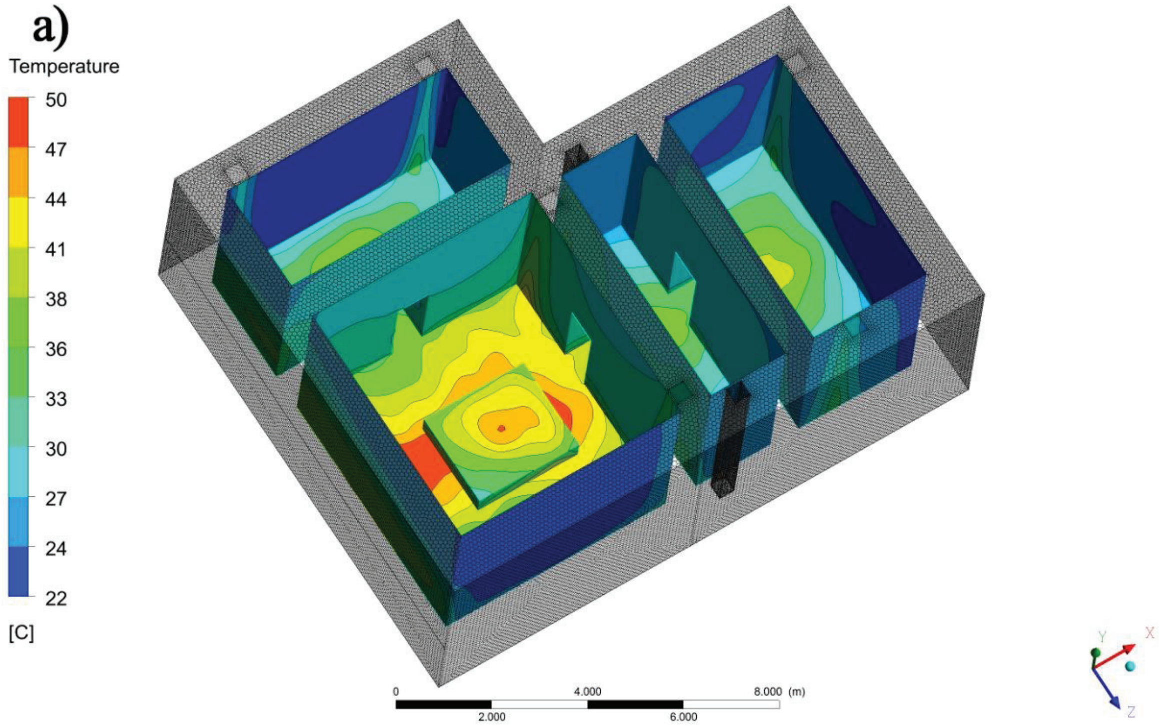


Figure 5.5. (Cont.)

Since, there is not any wall heating system in the bath (same as currently used system), temperature values are relatively low at the inner surfaces of the walls as can be seen in Figure 5.6. This temperature drop is significant because the wall surfaces are affected by the outside environment. But, inner walls are not effected too much because of relatively low heat loss. On the other hand, the chimneys embedded inside of the walls provide hotter surfaces and support the thermal condition of the bath.



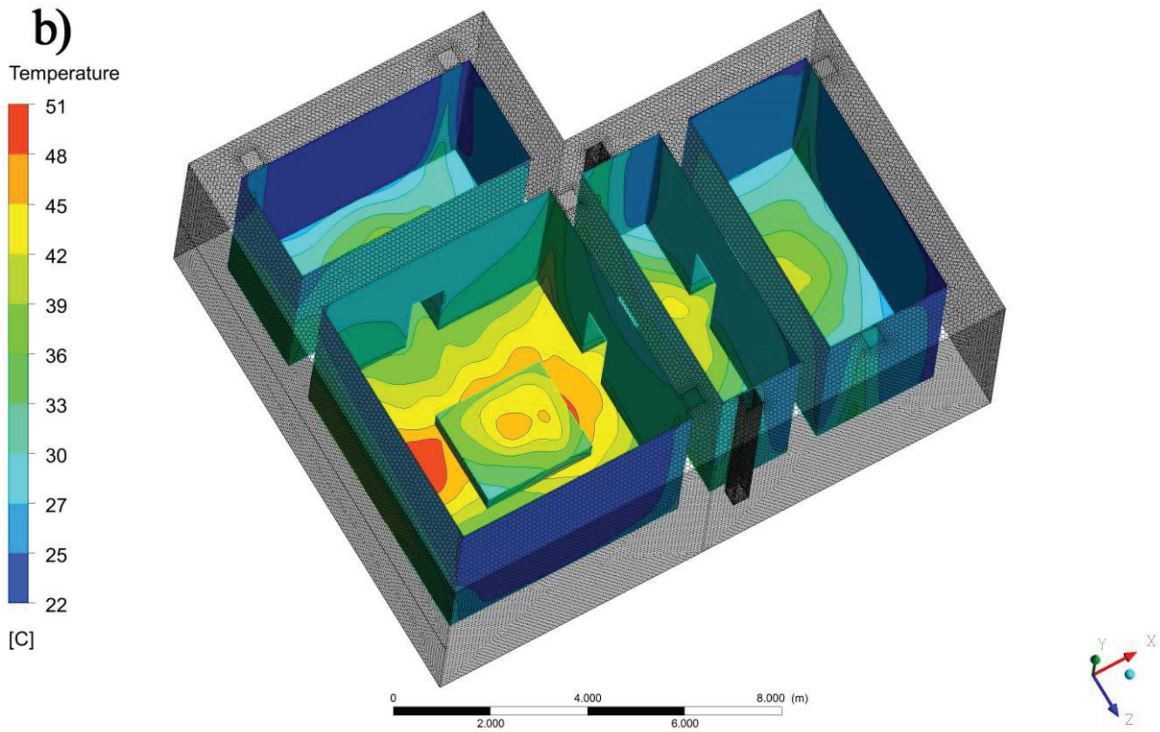


Figure 5.6. The temperature distribution on the walls and the floors for Scenarios a, b, c and d.

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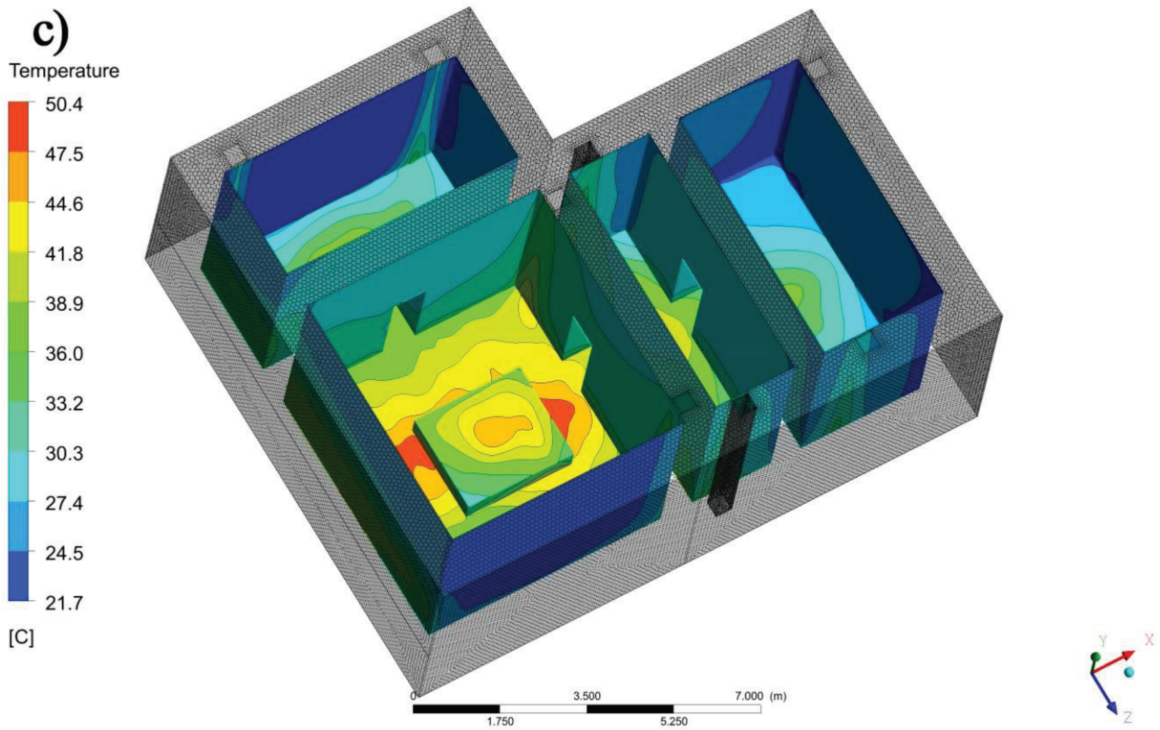

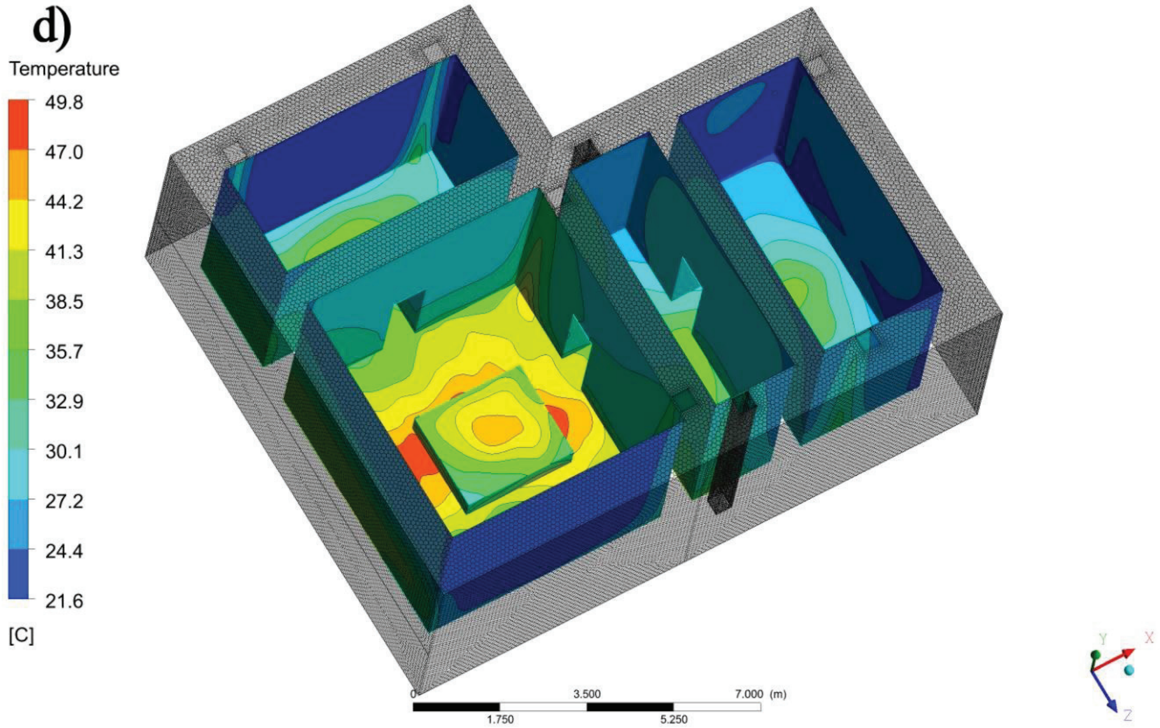

Figure 5.6. (Cont.).

The four scenarios have different indoor temperature distributions, thus they show differences at the temperature of the heated surfaces, as illustrated in Figures 5.7-12. In Figures 5.7 and 5.9, while the temperature value of the hot bath is around 31°C for Scenarios b and c, it is approximately 30°C in Scenarios a and d. On the other hand, temperature distributions of each sections is different from each other for the warm bath for four scenarios. These different temperature distributions also effect the heat transfer rates individually. According to the simulations, heat transfer rates are different for each scenario from floors to the rooms of the bath. Heat transfer rates are 1193.2 W for scenario a, 1239.1W for scenario b, 1221.6 W for scenario c and 1172.7 W for scenario d. In scenario b, heat transfer rate from floor to the rooms is calculated as the highest which show us the most energy efficient chimney configuration.

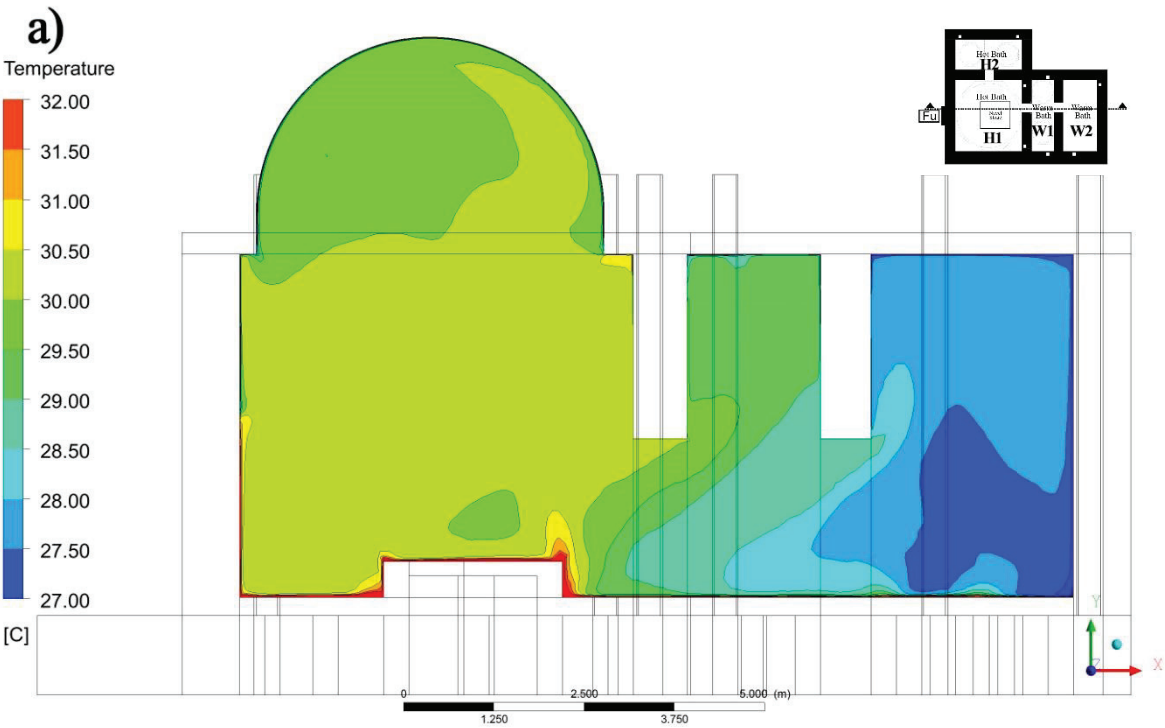

Figure 5.7. The temperature distribution in the x-y -plane for Scenarios a, b, c and d.

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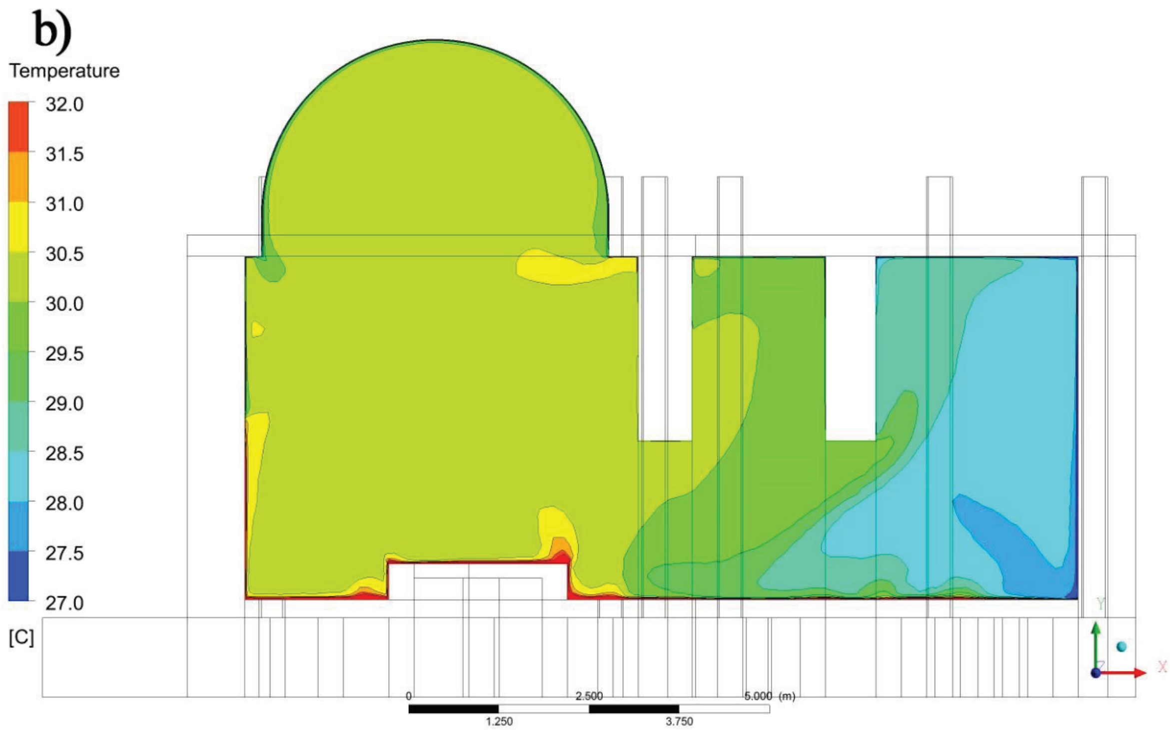

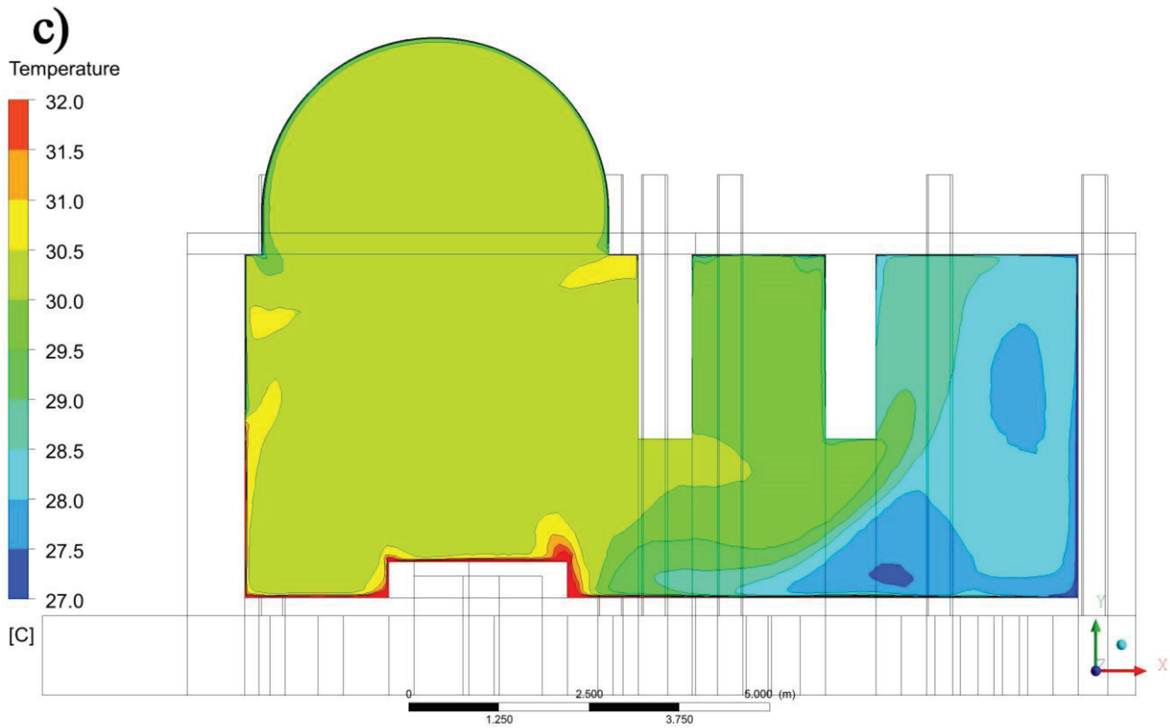

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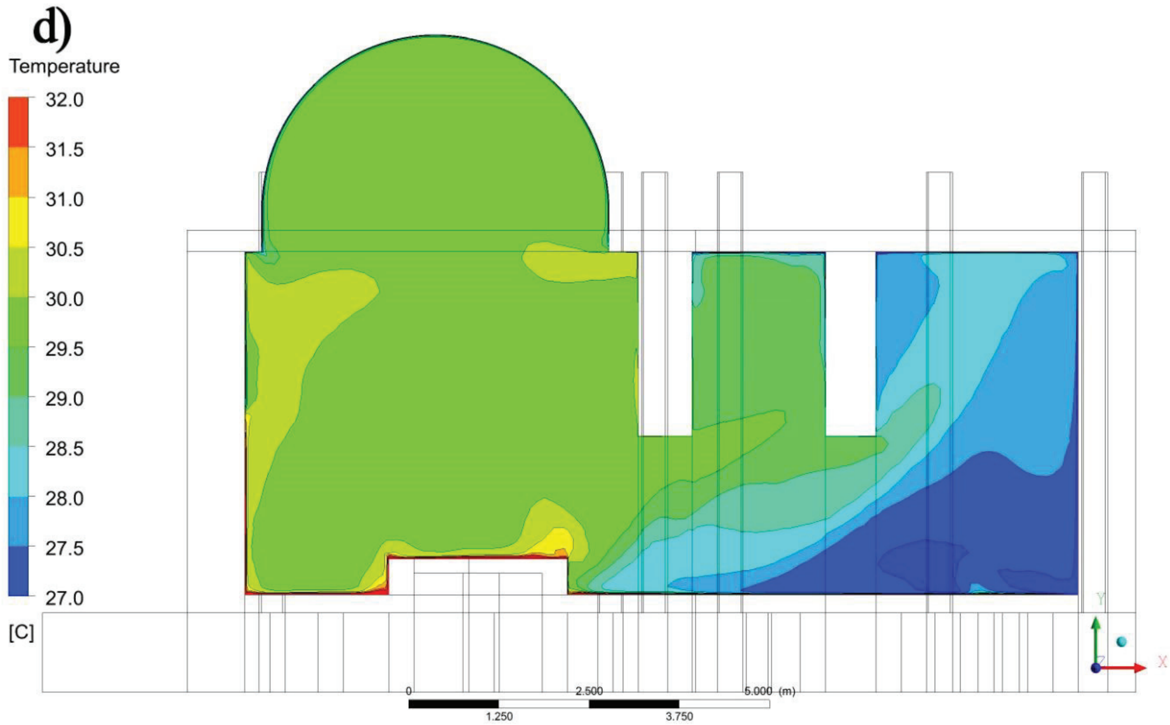

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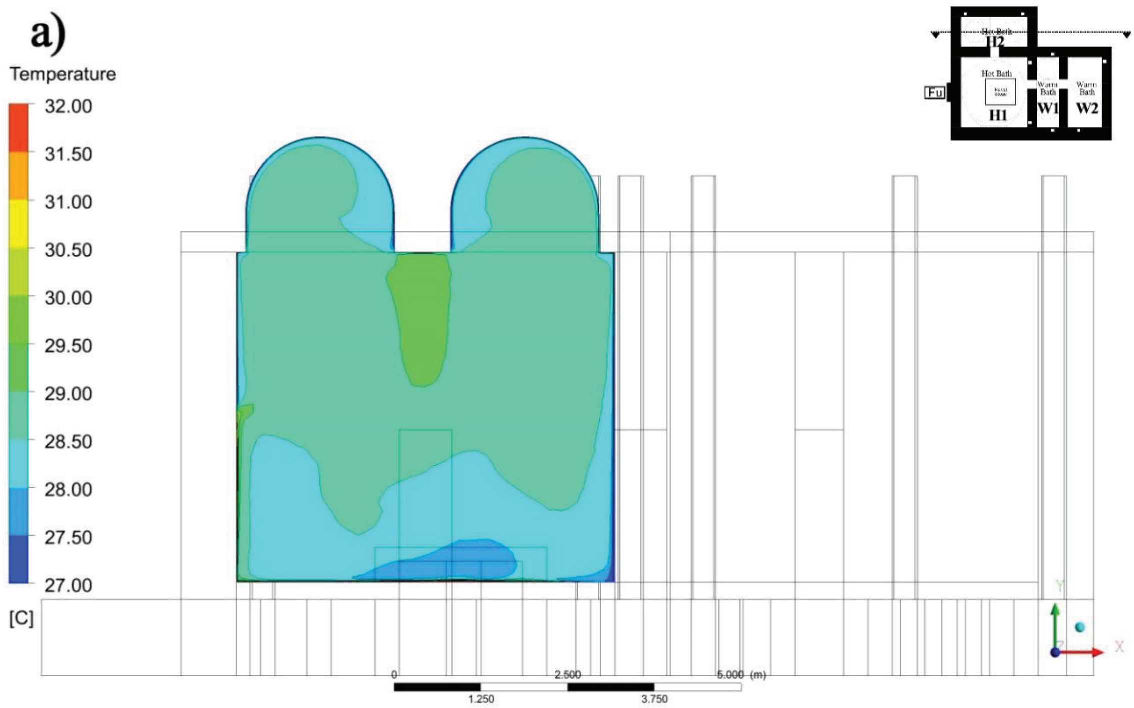

Figure 5.8. The temperature distribution in the the x-y-plane for Scenarios a, b, c and d.

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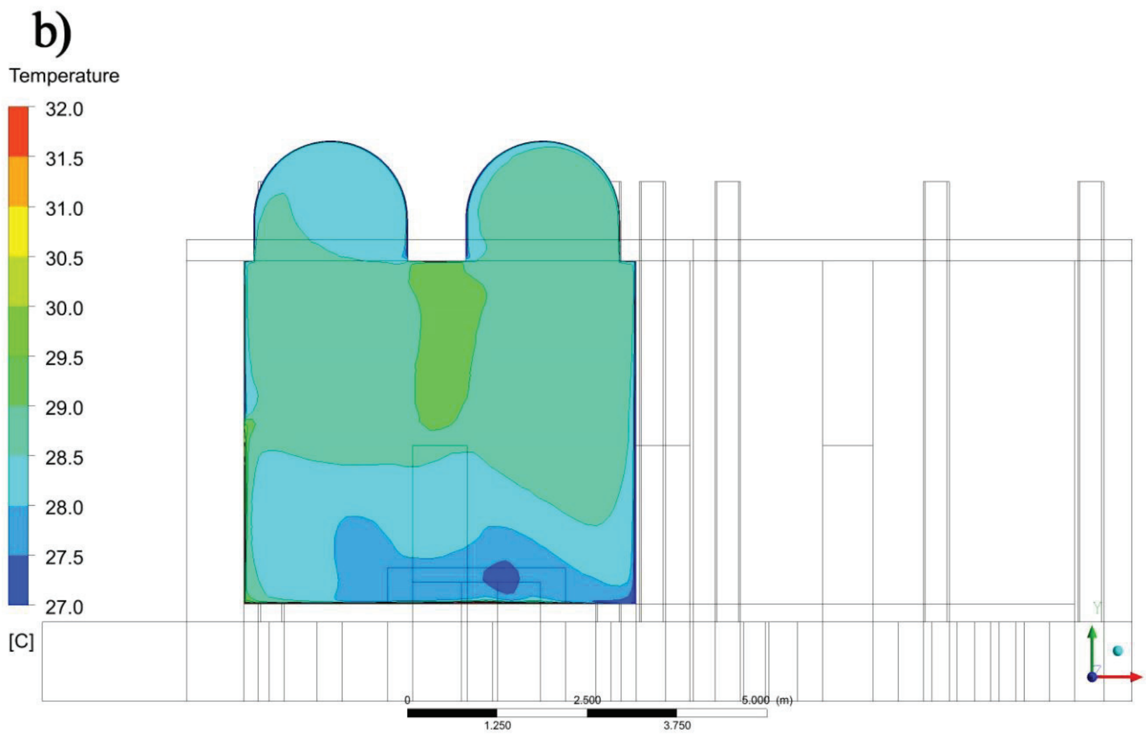

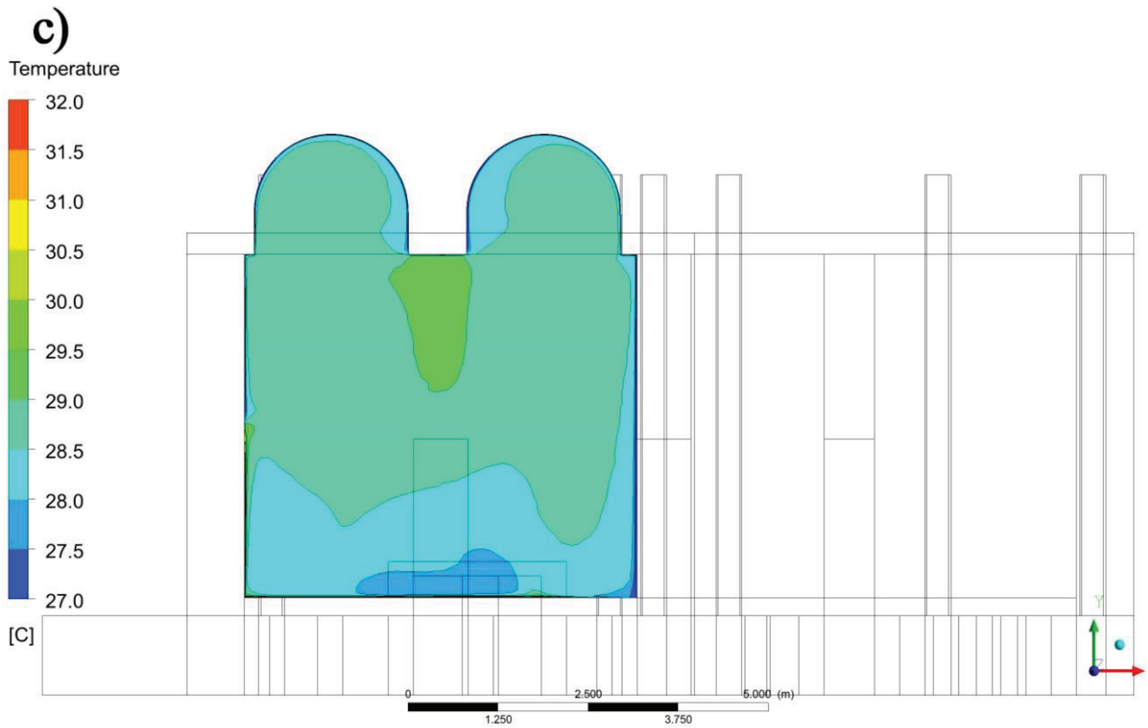

Figure 5.8. (Cont.).

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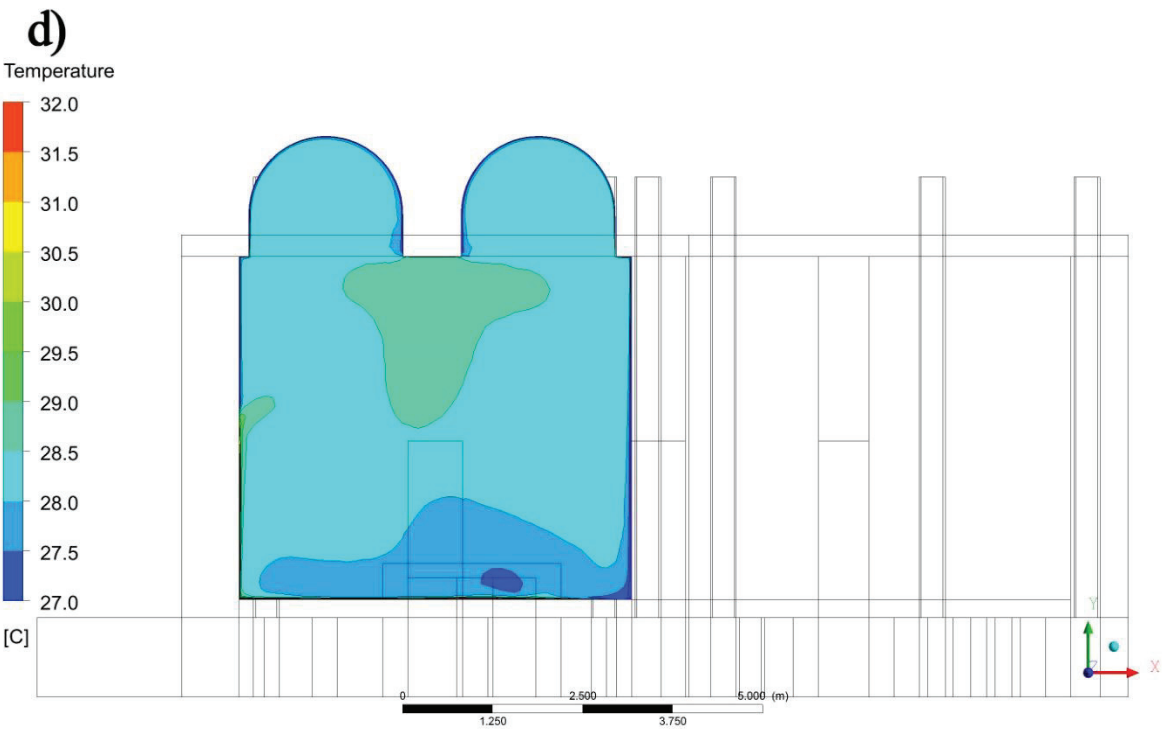

Figure 5.8. (Cont.).

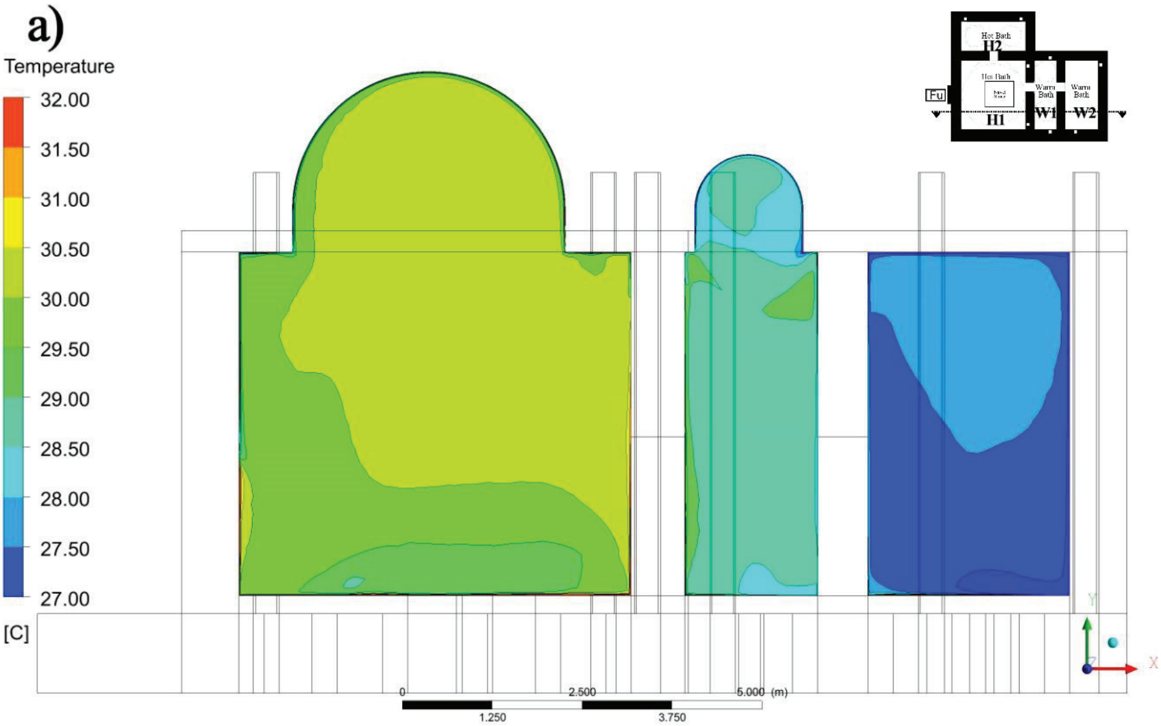

Figure 5.9. The temperature distribution in the x-y-plane for Scenarios a, b, c and d.

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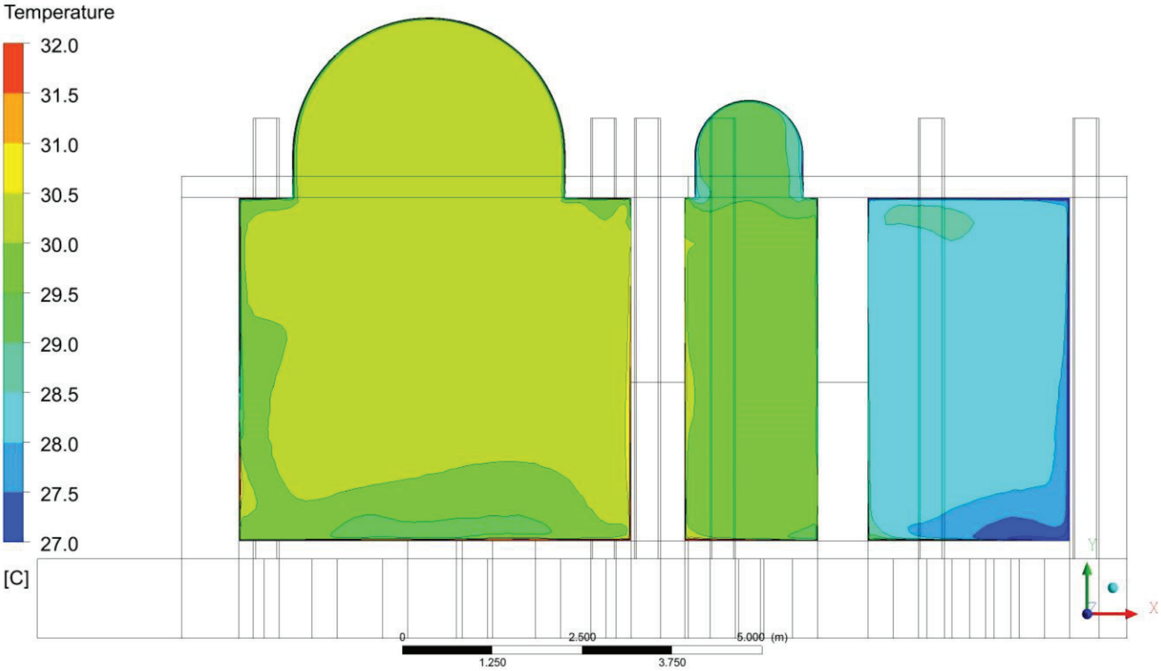
b)



c)

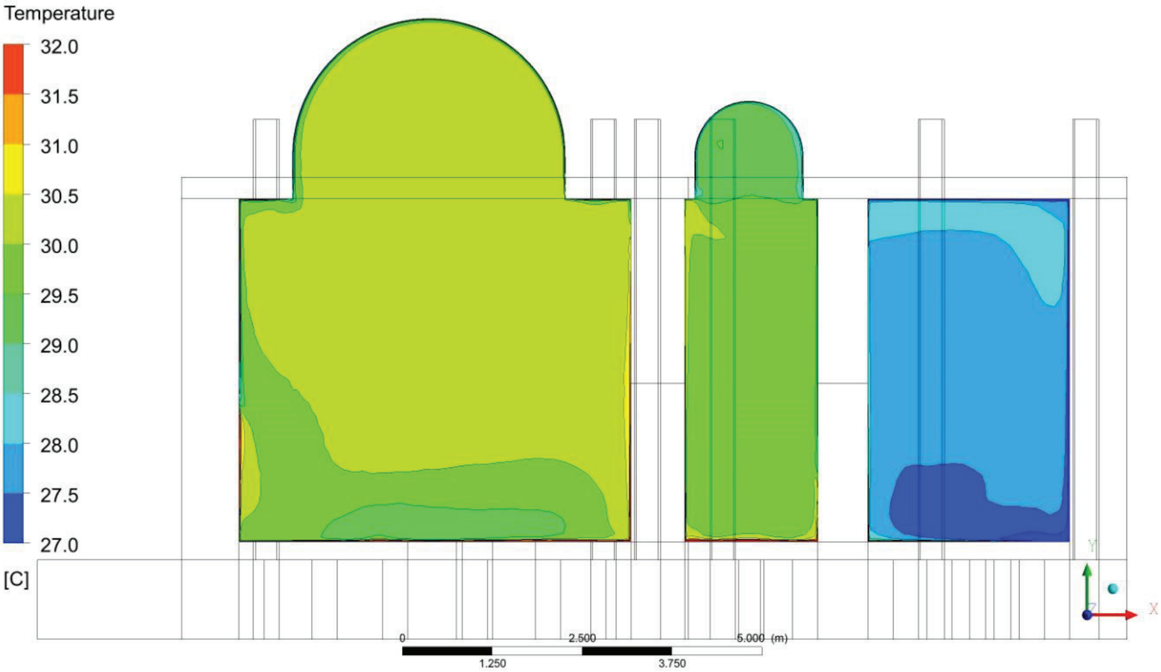


Figure 5.9. (Cont.).

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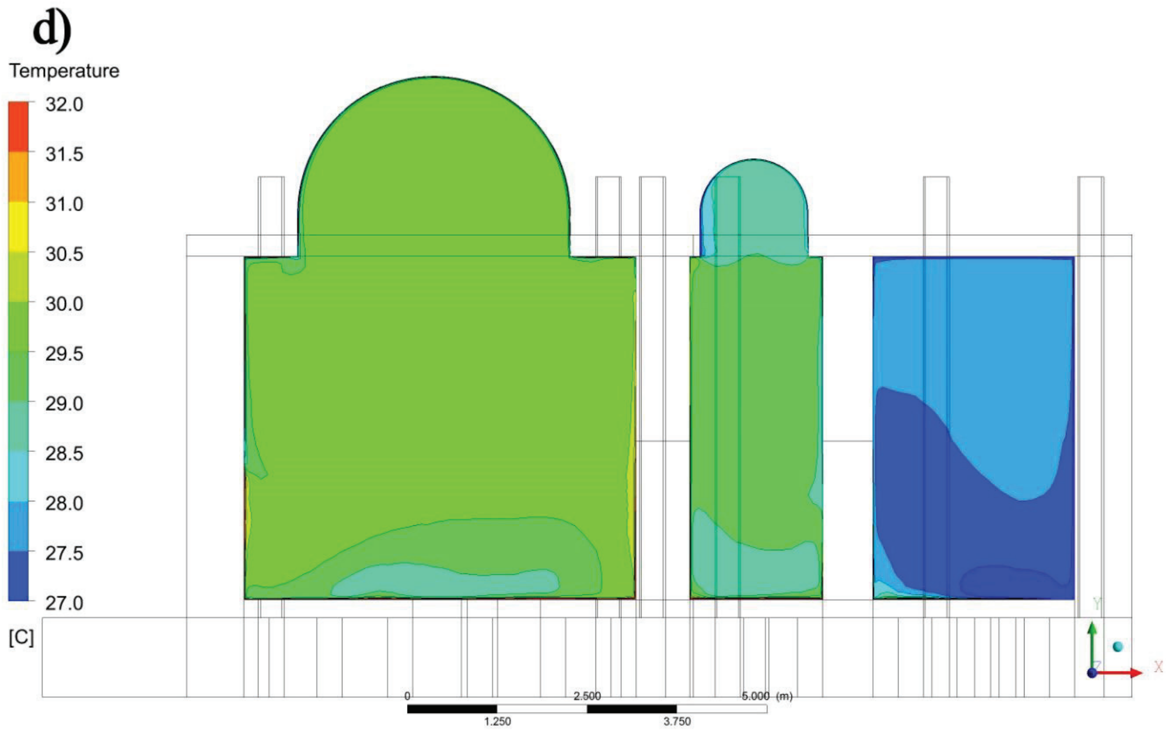
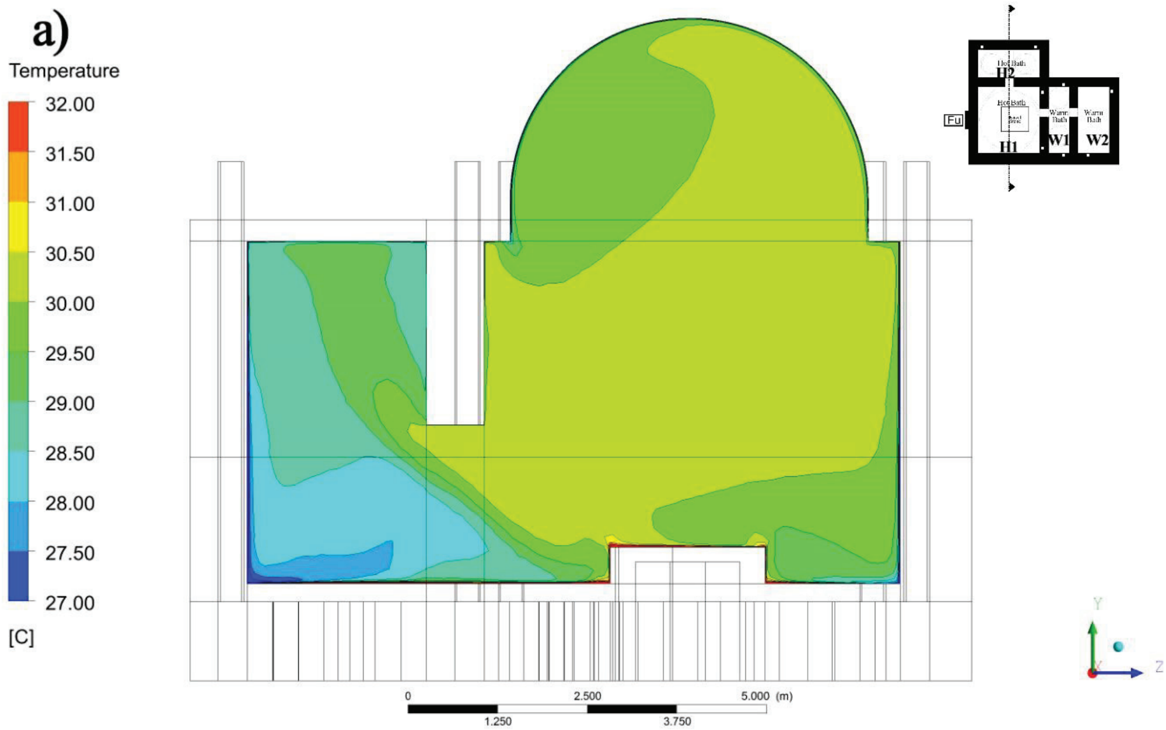


Figure 5.9. (Cont.)

In Scenarios a and d, temperature of the hot bath is lower than scenario b and c because of the fact that the energy of flue gas is not enough. In Figure 5.8, while in scenario d temperature distribution of hot bath is between 27.5°C and 29°C because of the location and number of the chimney, in other scenarios this value is as high as 30°C.

In Figure 5.10, we can see the temperature distribution at the sections of two hot baths. In Scenarios a and b, temperature distribution and values are similar to each other. On the other hand, the temperature value is lower than 1°C in scenarios c and d.



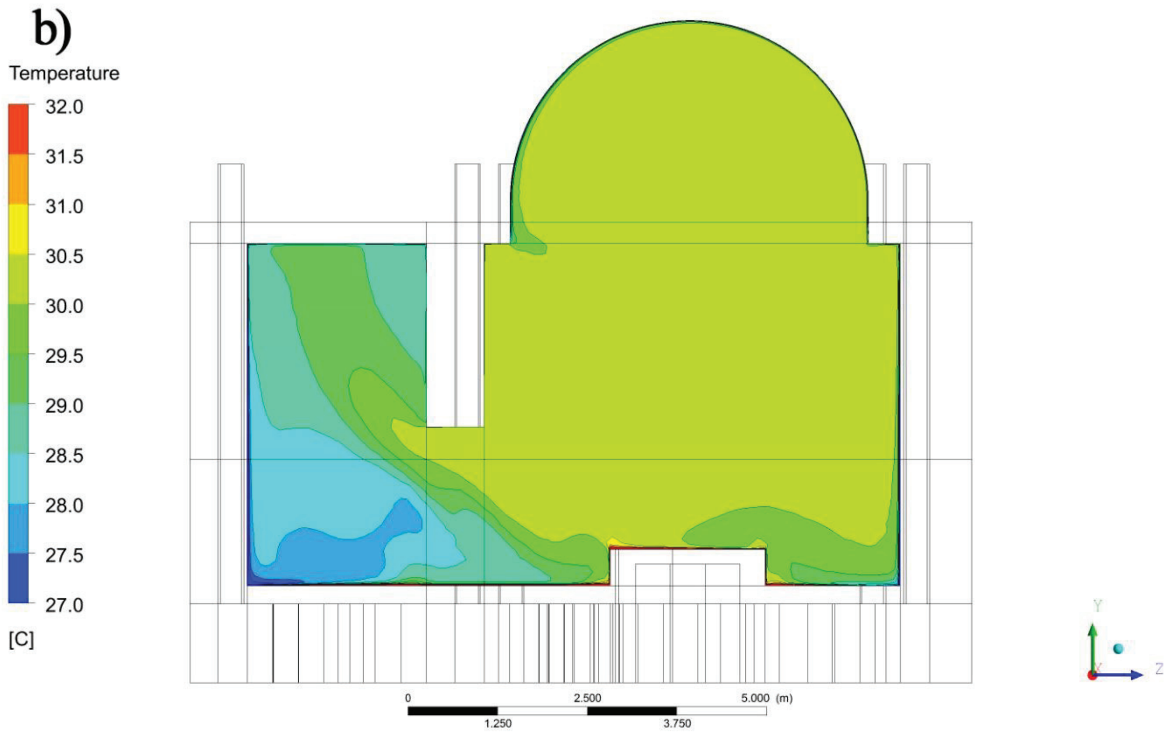


Figure 5.10. The temperature distribution in the y-z-plane for Scenarios a, b, c and d.

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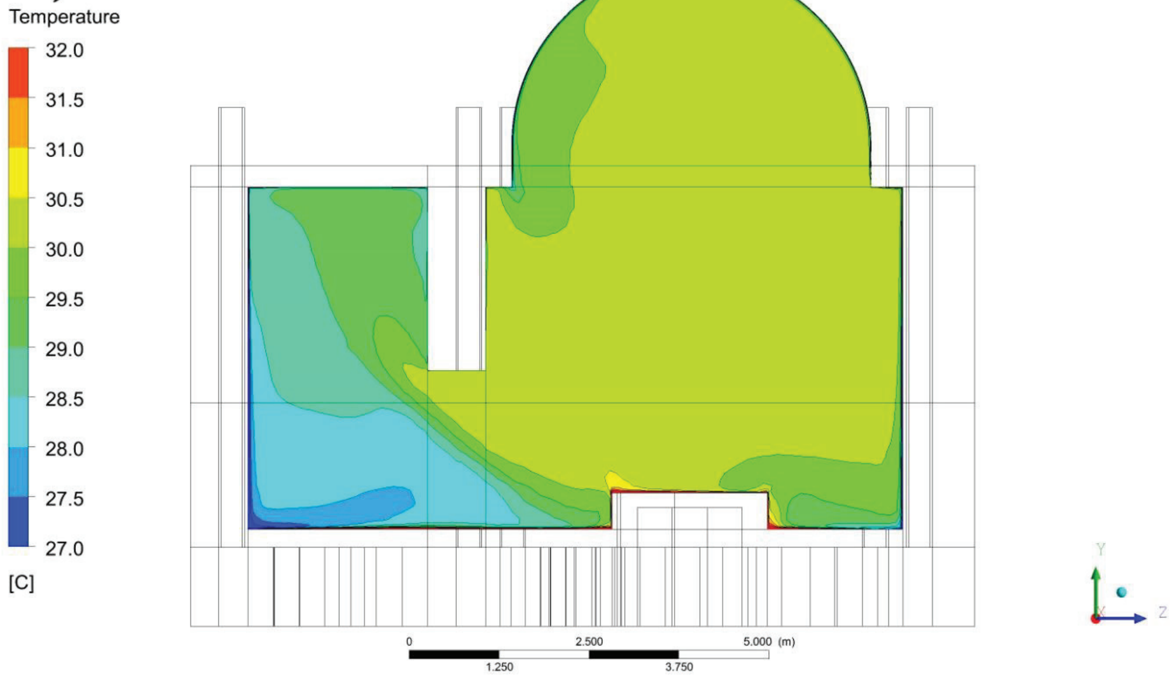
c)



d)

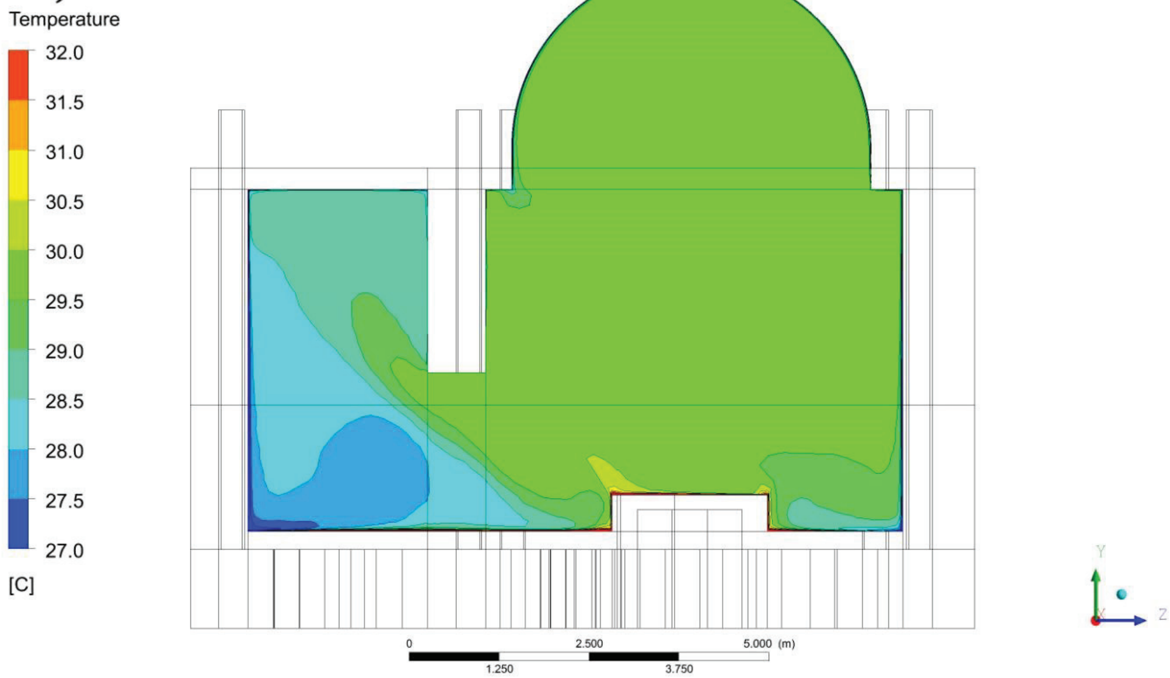


Figure 5.10. (Cont.).

Moreover, in the warm bath, the temperature values and distributions show similarities in Scenarios b and c in contrast to Scenarios a and d (Figure 5.11). On the other hand, different distributions and curves appear differently for each scenario for the warm bath (W1).The temperature distribution is observed between 27°C and 29.5°C and shown in Figure 5.11.

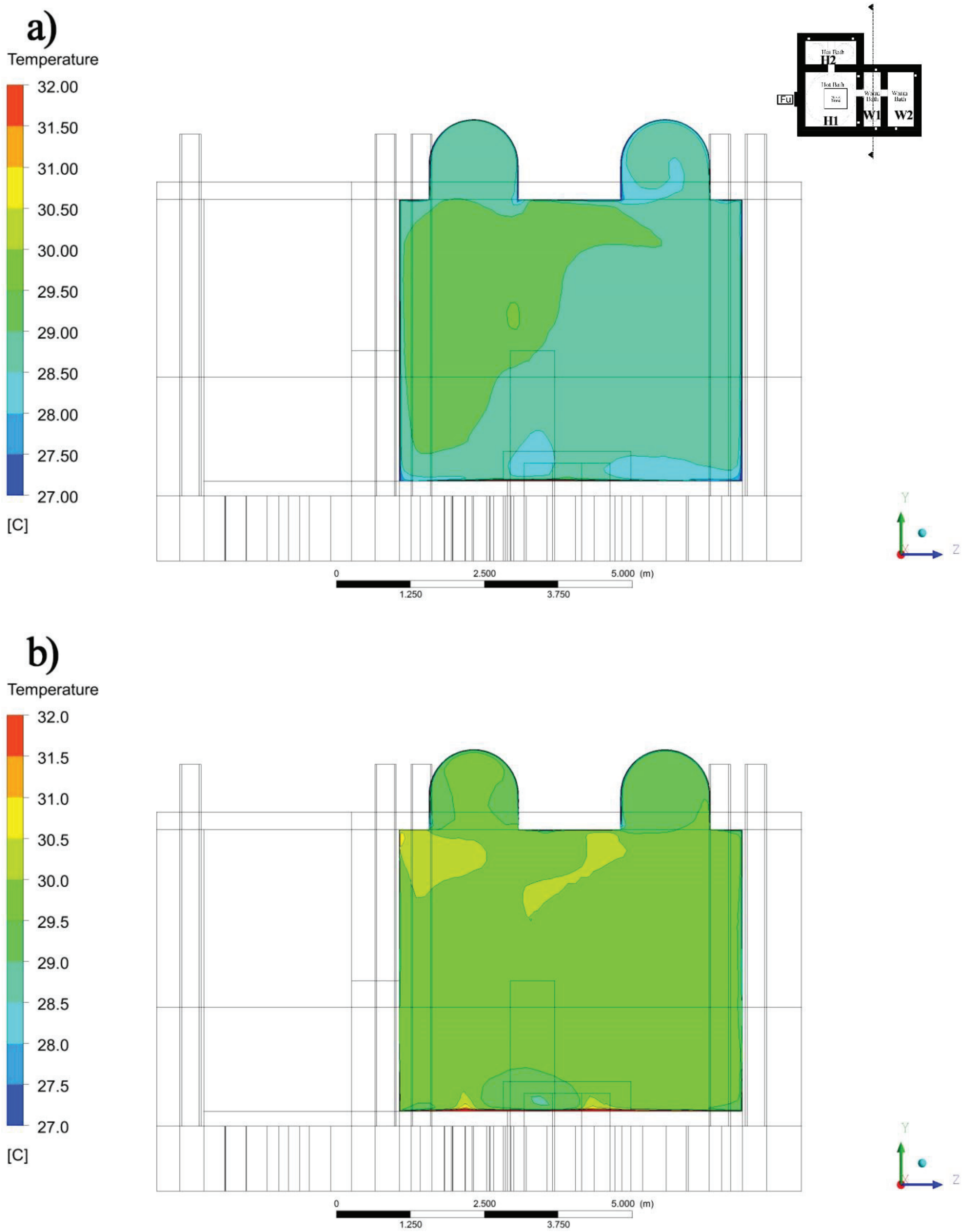


Figure 5.11. The temperature distribution in the y-z-plane for Scenarios a, b, c and d.

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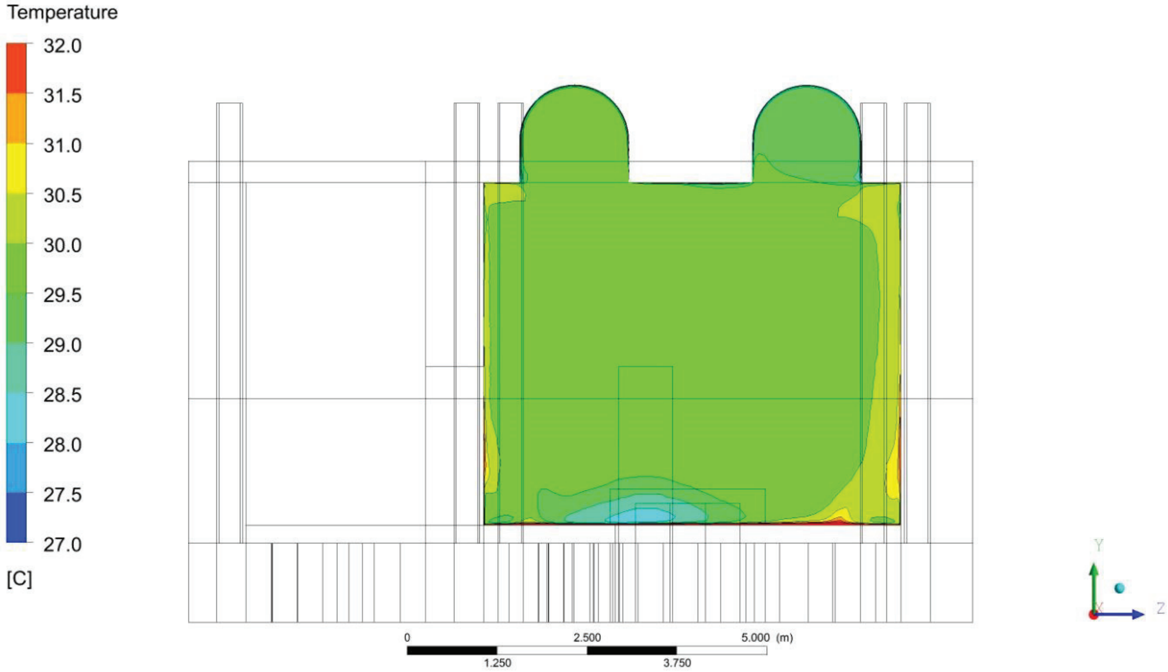
c)



d)

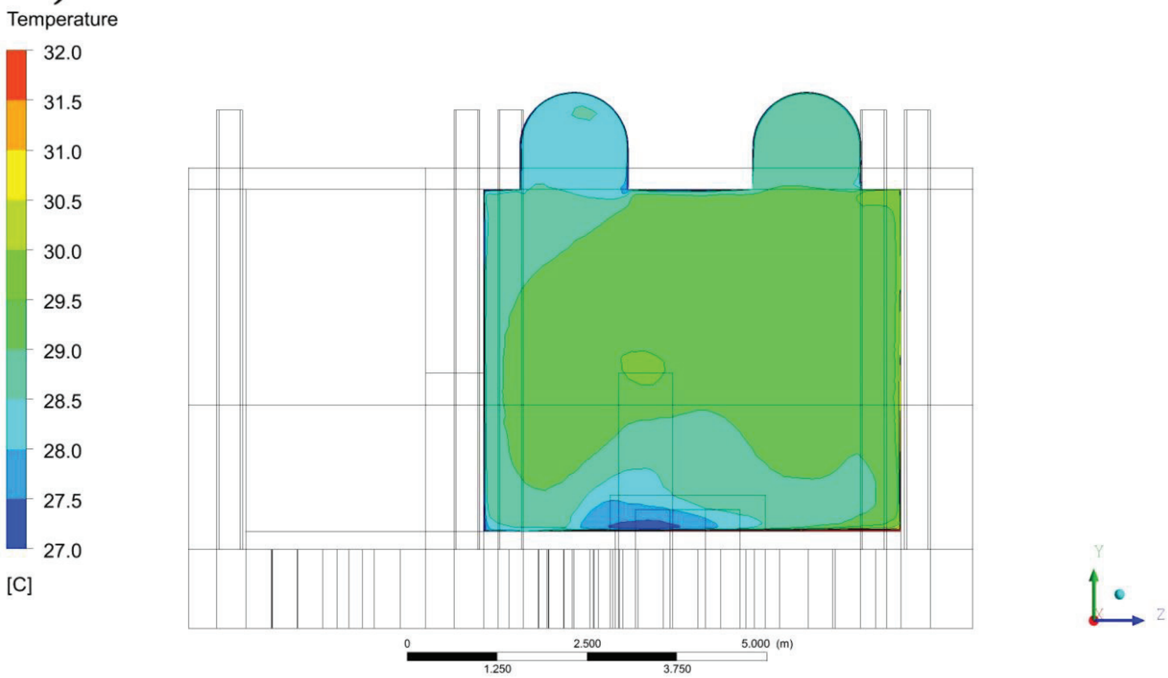
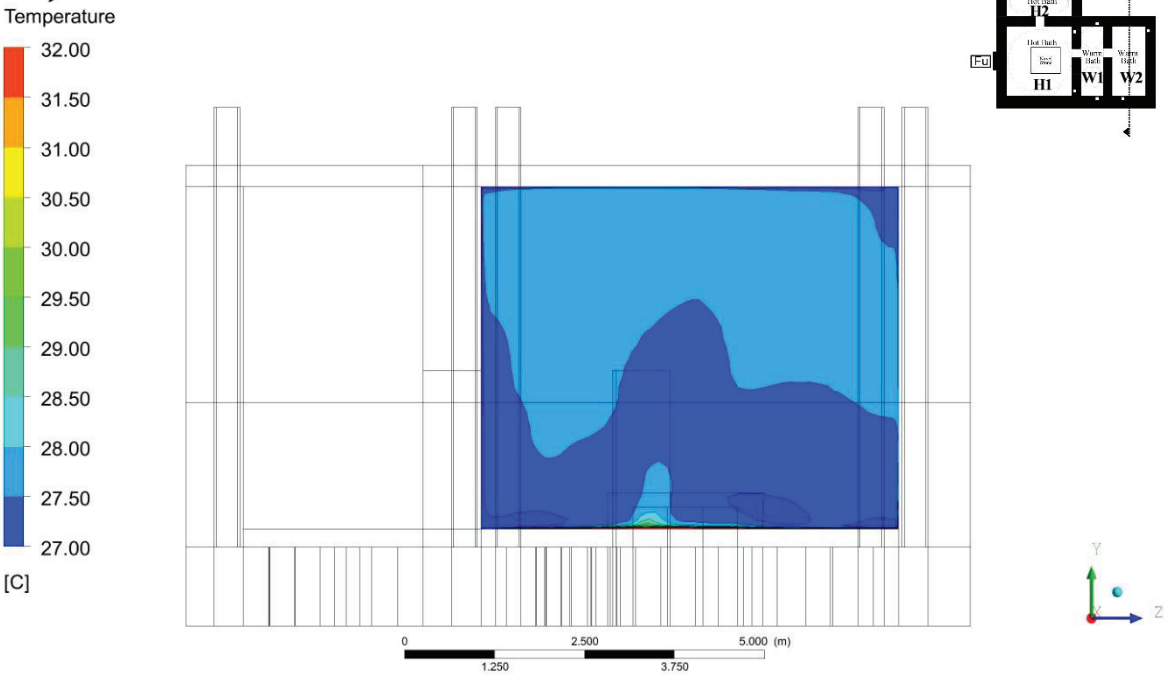


Figure 5.11. (Cont.).

a)



b)

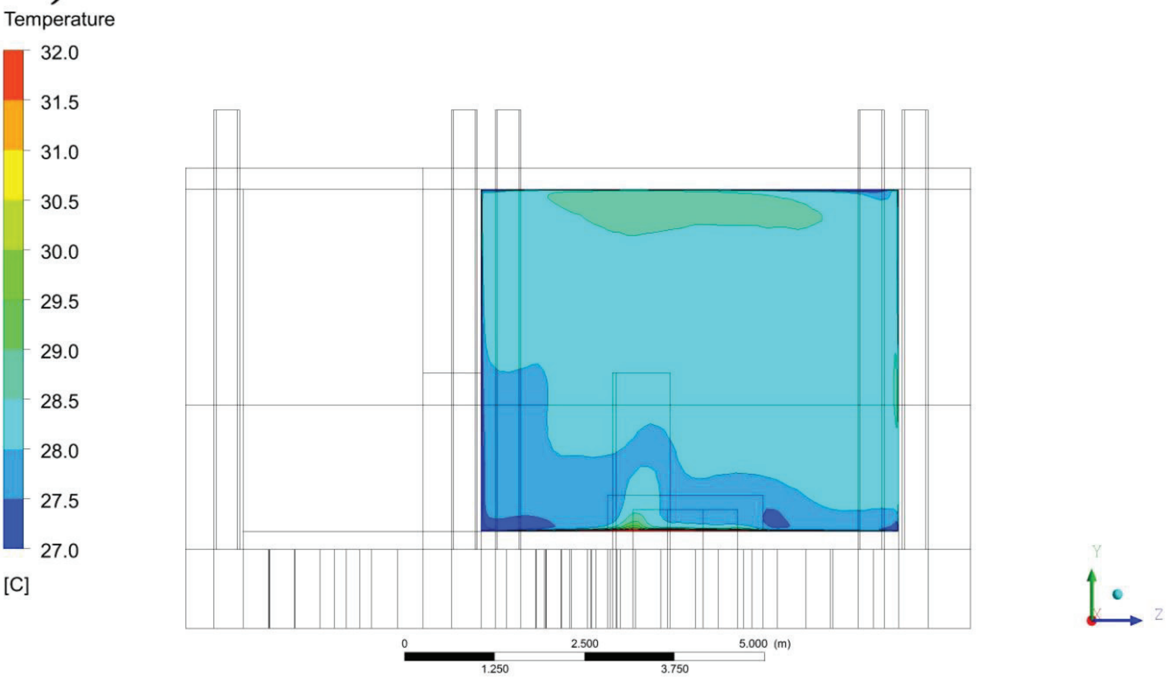


Figure 5.12. The temperature distribution in the y-z-plane for Scenarios a, b, c and d.

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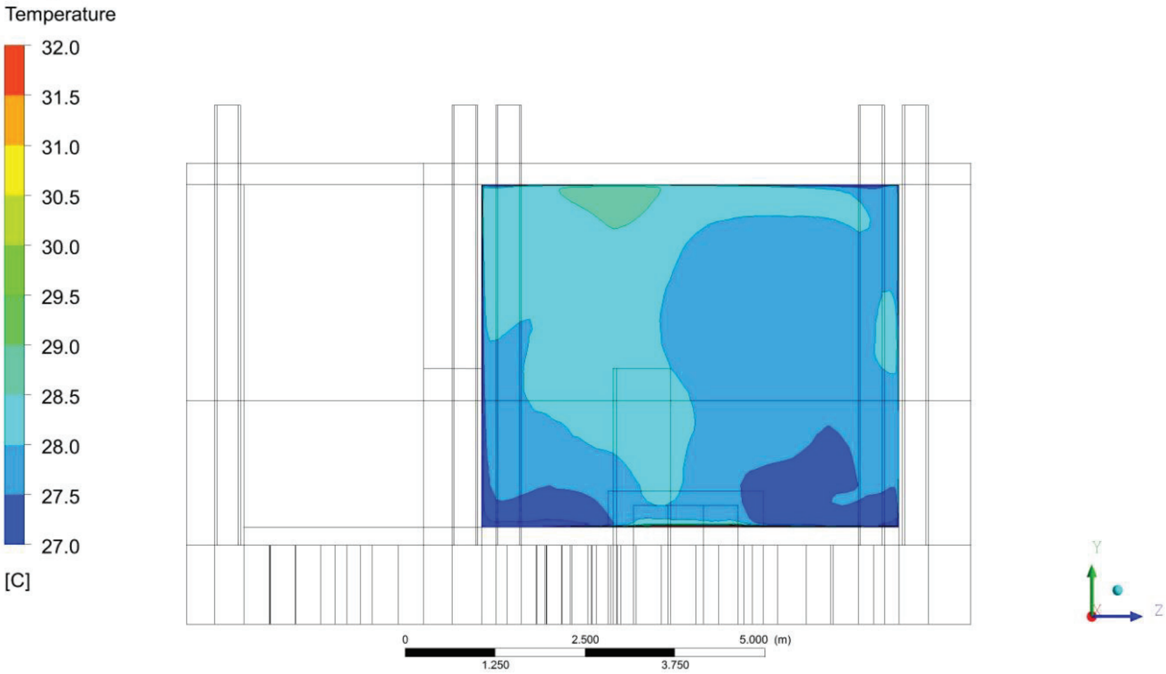
c)



d)

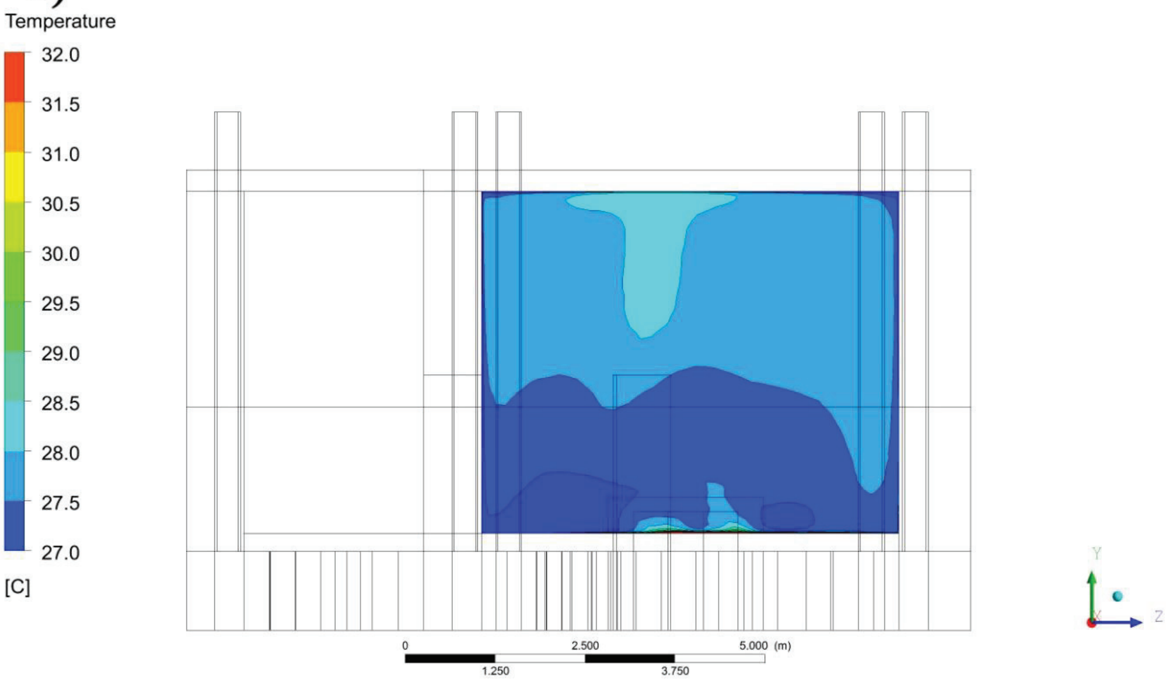
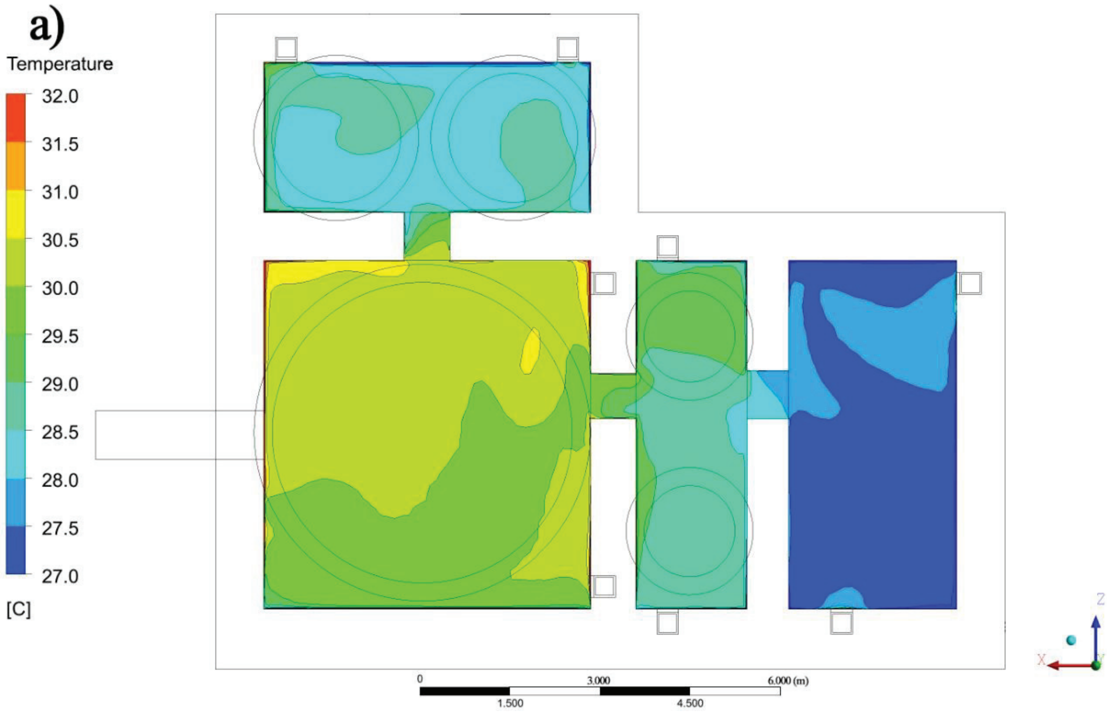


Figure 5.12. (Cont.).



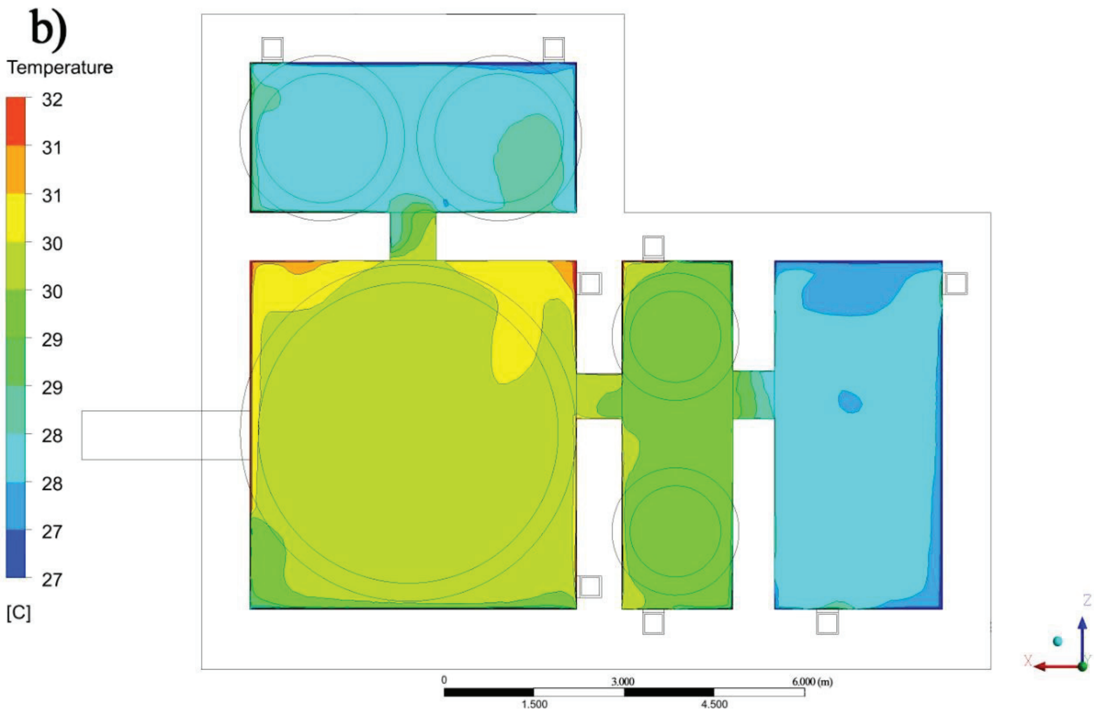


Figure 5.13. The temperature distribution in the x-z-plane for scenarios a, b, c and d.

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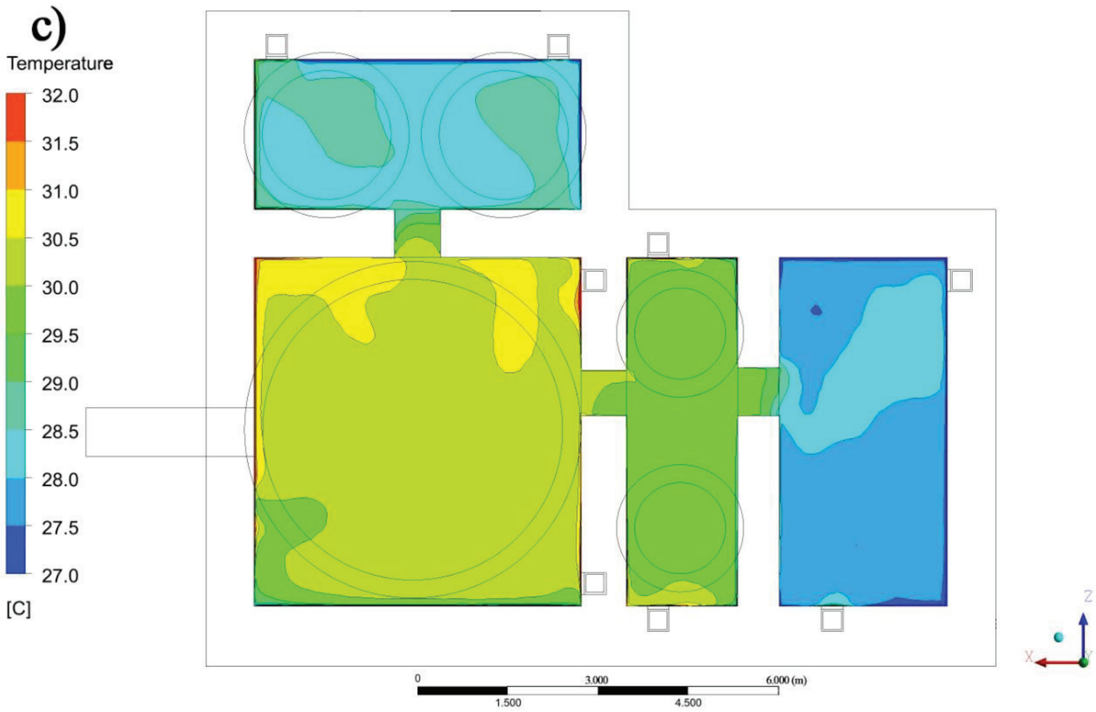


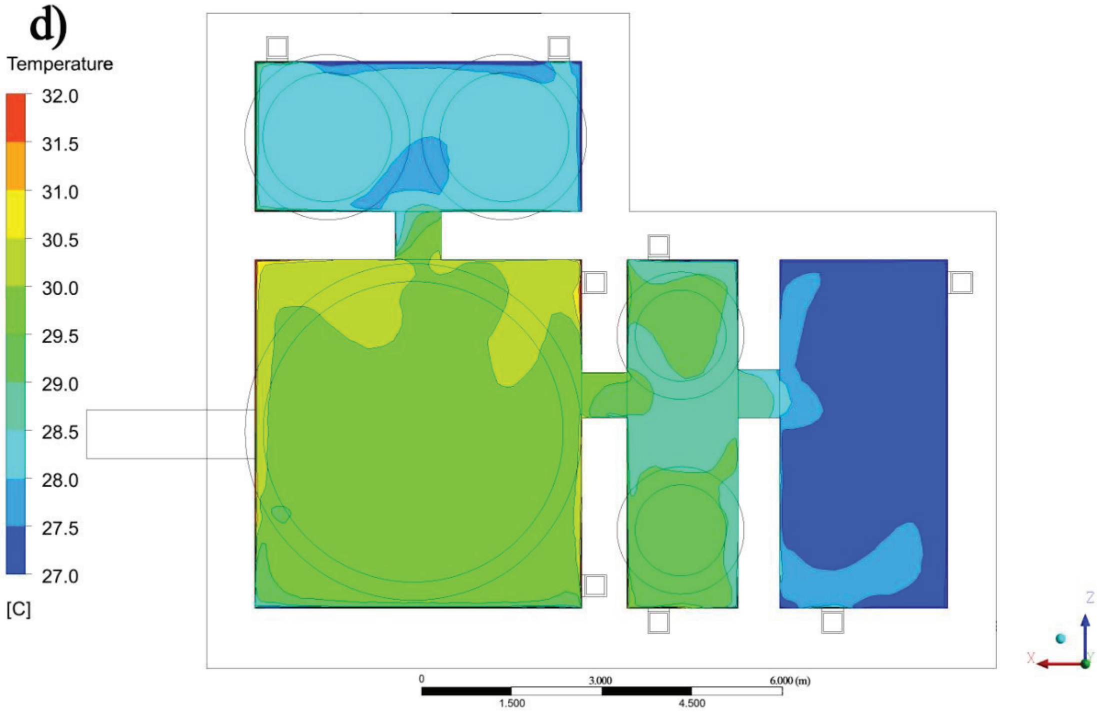
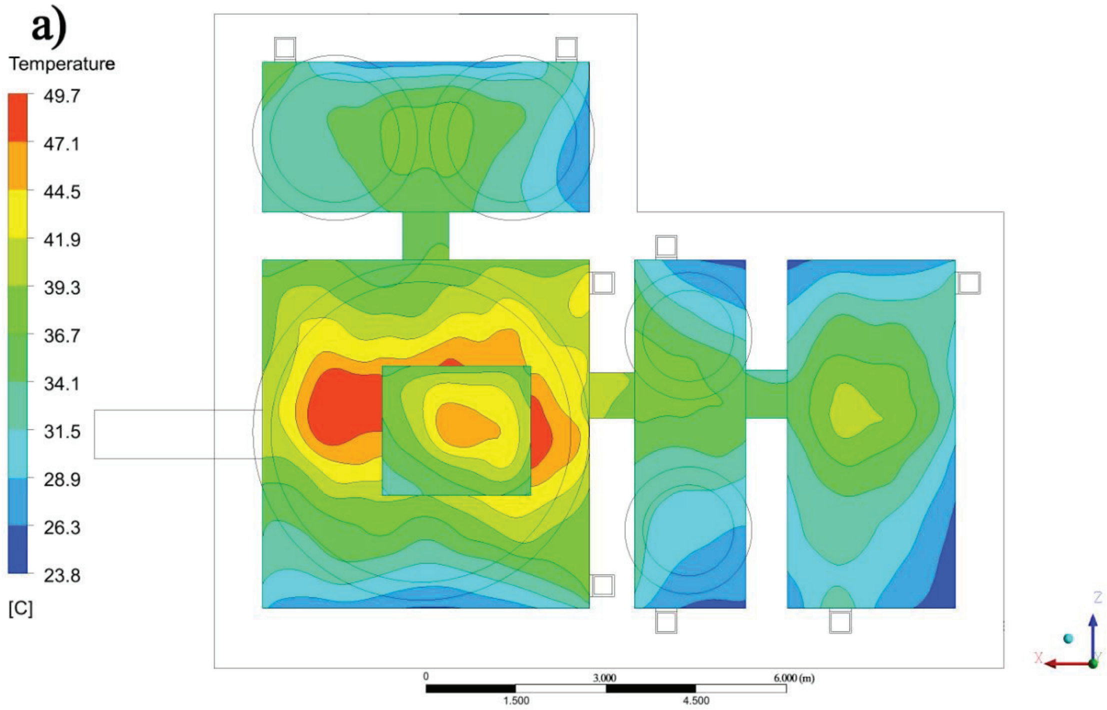


Figure 5.13. (Cont.).

The average temperature of the heated floor of the hot bath is the lowest for scenario d, i.e. on average around 29.5°C. This temperature is different in Scenarios b and c where the floor temperature reaches the highest values i.e. about 31°C (Figure 5.14).



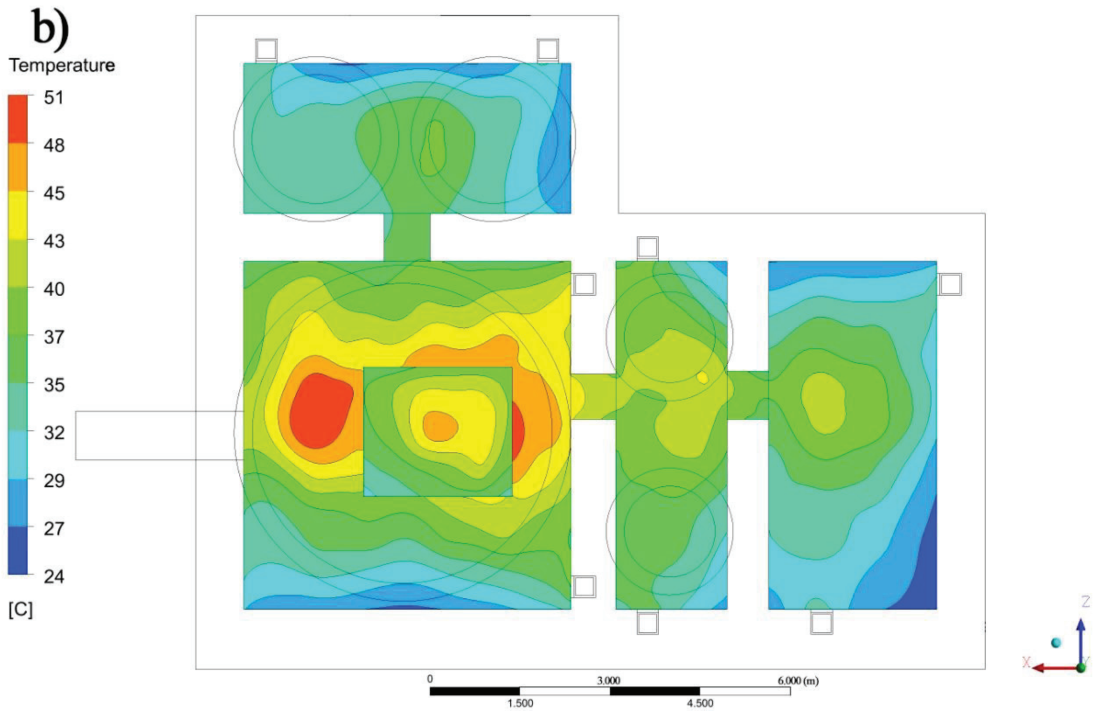


Figure 5.14. The temperature distribution on the floor for Scenarios a, b, c and d.

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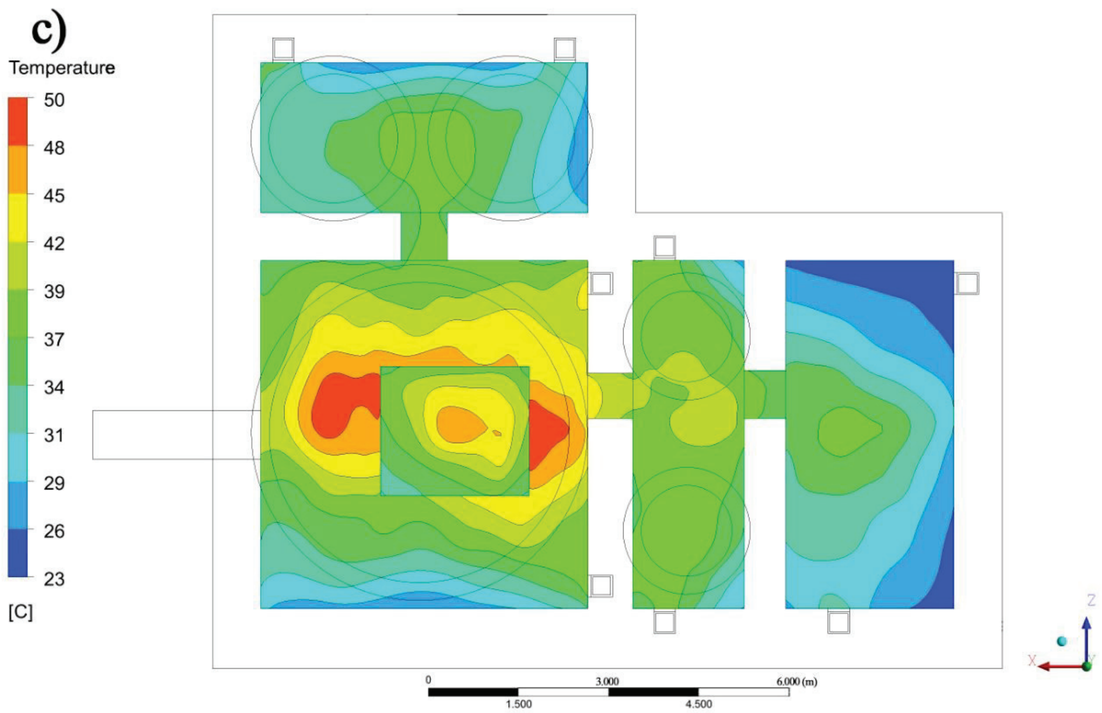

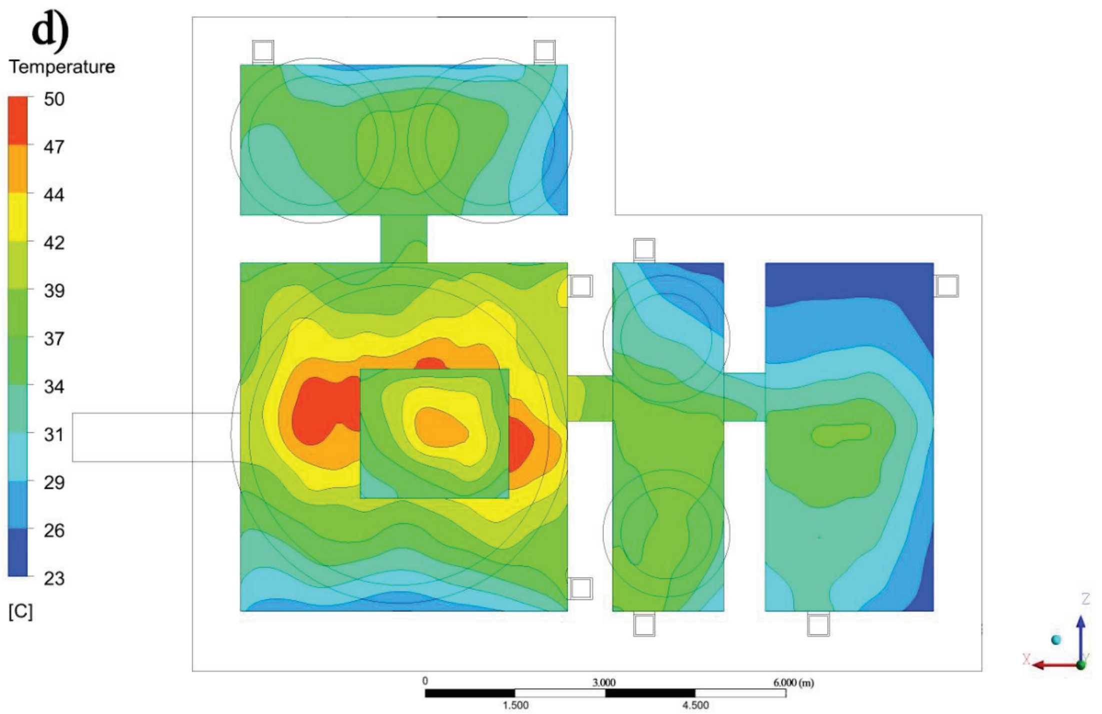

Figure 5.14. (Cont.).

According to the results discussed above, Scenarios b and c reflect almost similar temperature distribution behavior. An outdoor temperature of 8.8°C was considered for all scenarios. The indoor average temperatures of the baths vary between 29.5°C-31°C for four scenarios and in the coldest part of the bath, the minimum temperature is 27°C. Yegül states that in the *caldarium*, air temperature should be close to human body temperature, which is around 37°C. If the air temperature is higher, it will cause thermo-physiological discomfort [45].

The mass flow rates for four different chimney configurations are given in Table 5.1 from the furnace to the chimneys numbered t1-t8. The same inlet mass flow rate of 0.17 kg/s was used for the all scenarios which is calculated by using uniform velocity value, given in the code as a boundary conditions. Mass flow rate in Equation 5.1 is calculated by using the uniform inlet velocity (0.2 m/s), the furnace cross-section area (0.9 m^2) which is perpendicular to the velocity vector and the flue gas density (assumed as 0.972 kg/m^3 based on the atmospheric air temperature of 90°C).

$$\dot{m} = \rho A_c V_{avg} \tag{5.1}$$

The flow rate which enters to the hypocaust system (0.17 kg/s), exhausts through the chimneys numbered t1-t8, hence the mass is conserved as can be seen in Table 5.1. Due to the conservation of mass, the flue gas flow rate from each chimney depends on the number of chimneys numbered t1 to t8 for all scenarios. So, the inlet mass flow rate is almost divided individually by the equal amount of flue gas exhaust from chimneys. This inlet mass flow rate value is obtained from the fuel, mainly wood, and air, in order to provide necessary energy for heating up of the bath sections by the system with the hypocaust.

Table 5.1. Mass flow rates in kg/s from the furnace (Inlet) to the chimneys (t1-t8) and mass flow rate fraction.

	Inlet	t1	t2	t3	t4	t5	t6	t7	t8
Scenario a	0.17	0.0281 %16.5	0.0282 %16.5	0.0287 %16.9	0.0293 %17.2	-	-	0.0283 %16.6	0.0284 %16.7
Scenario b	0.17	0.0215 %12.6	0.0215 %12.6	0.0220 %12.9	0.0227 %13.3	0.0200 %11.8	0.0200 %11.8	0.0217 %12.8	0.0218 %12.8
Scenario c	0.17	0.0243 %14.3	0.0244 %14.3	0.0249 %14.6	0.0257 %15.1	0.0235 %13.8	0.0234 %13.8	-	0.0245 %14.4
Scenario d	0.17	0.0280 %16.5	0.0281 %16.5	0.0287 %16.9	0.0292 %17.2	-	0.0283 %16.6	-	0.0286 %16.8

The rate of energy values for four different chimney configurations are given in Table 5.2. The inlet energy rate from the furnace to the hypocaust system is 11,191 W for all scenarios. Some portion of this inlet energy rate is sent from the hypocaust to the bath floor, while the other portion is dissipated to the outside environment through the chimneys numbered t1-t8. Remaining portion of the energy rate (ΔE) is conserved in the water tank, ground and the wall surfaces etc. of the bath. Heat transfer rates which penetrate from the floor to the rooms of the bath are 1193.2 W for scenario a, 1239.1 W for scenario b, 1221.6 W for scenario c and 1172.7 W for scenario d. Energy rate from the furnace to the hypocaust system and the dissipated energy to the outside environment through the chimneys are calculated by Equation 5.2:

$$\dot{E} = \dot{m} C_p T \tag{5.2}$$

Table 5.2. Amount of heat transfer rate in W from the furnace to the different sections of the bath.

	to hypo.	**from floor**	**from t1**	**from t2**	**from t3**	**fro m t4**	**fro m t5**	**from t6**	**from t7**	**from t8**	**ΔE**
Scenario a	11,191	1,193	606	570	950	859	-	-	578	560	5,875
Scenario b	11,191	1,239	381	382	674	603	467	415	423	417	6,190
Scenario c	11,191	1,221	462	468	780	719	570	534	-	442	5,994
Scenario d	11,191	1,172	599	575	952	849	-	700	-	527	5,816

Considering inlet energy rate of the bath as 11,191 W given in Table 5.2, only energy transfer rate from the floor to the heated rooms is the available energy for heating up the bath. The other values mentioned as t1 to t8 and some portion of ΔE are the waste energy rates. So, the efficiencies of the heating systems are calculated as 10.7%, 11.1%, 10.9% and 10.5% for the Scenarios a, b, c and d, respectively.

Remaining portion of ΔE is used for heating the water in the tank as a useful energy rate which is not considered for the efficiency calculations.

5.2. The Floor Heating System

In the floor heating system, hot water in the pipes circulates under the floor to heat up the bath. Pipe system is required water temperature around 55°C for heating the bath. Based on this information, 3D simulation of the heating system is modeled in the CFD Environment to study fluid flow and the thermal behavior of the bath. In this numerical analysis, heat flux values at the floor surfaces are defined as 60 W/m^2 and 30 W/m^2 for hot and warm baths, respectively, as the boundary conditions.

In the section of the bath, the velocity vectors have shown graphically as a result of running the code as shown in Figure 5.15. The hot air flowing from the floor tries to reach to the dome by the buoyancy forces induced by the air density gradients and hot air starts to cool down and returns to the floor. Heat transfer rate is spread more homogenously from the floor because of defined constant heat flux values. In addition to this, while the hot air is passing from the gate between volumes, the velocity increases at the gate because of the differences of cross-section area. Temperature differences between hot and warm baths seen in Figure 5.16 are one of the main driving force for fluid flow. Air flow direction is from warm to hot room at the lower side close to the floor surface, and the flow turns back to the higher level as seen in Figure 5.15.

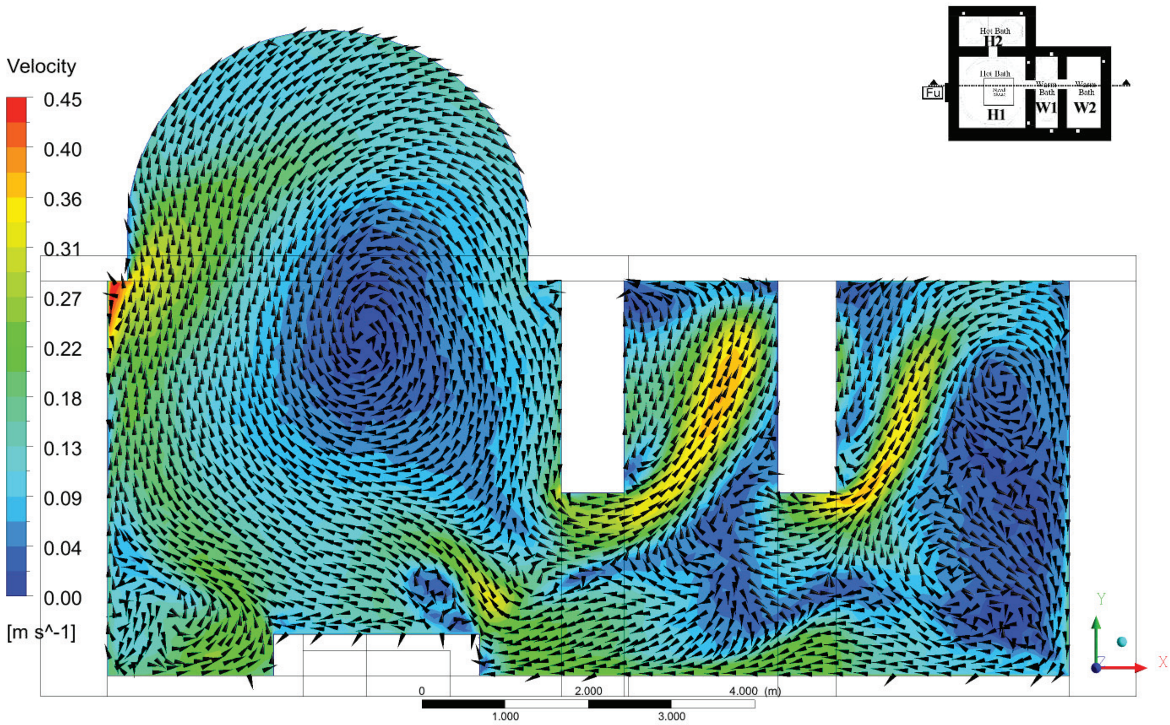

Figure 5.15. The velocity vectors in the x-y-plane.

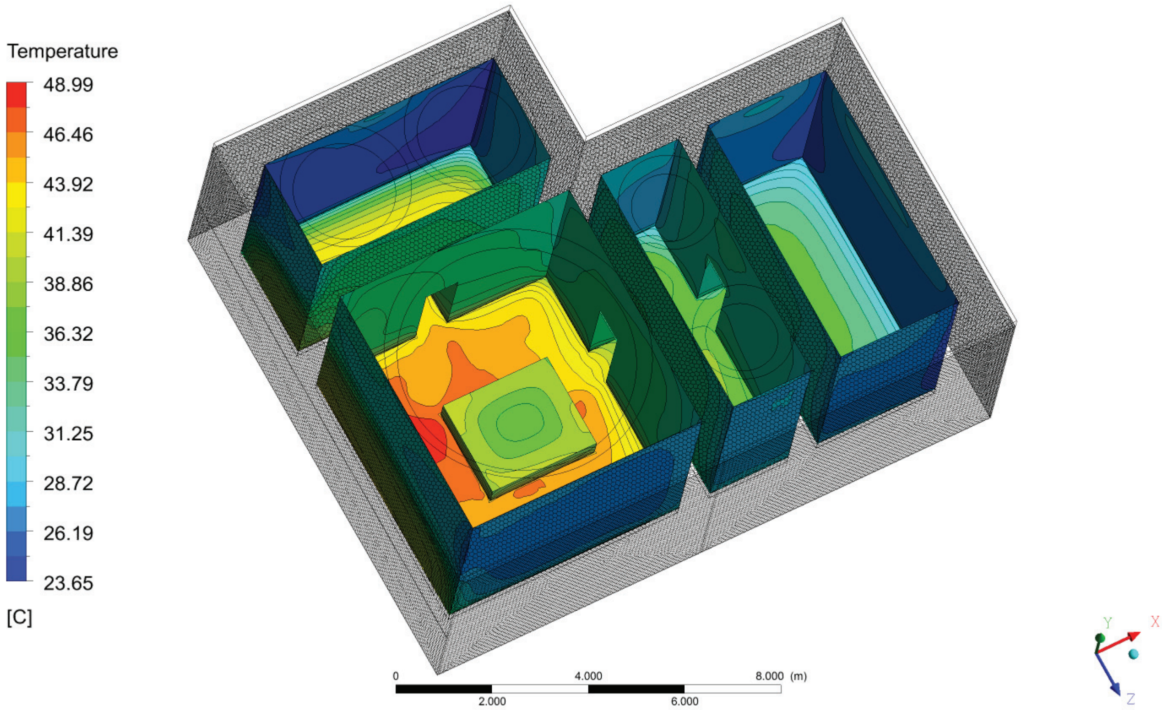

Figure 5.16. The temperature distribution on the wall and floor surfaces.

The temperature distribution at many sections of the bath are given in Figures 5.16-5.22. The air temperatures are observed between 34.20°C and 35.40°C in the hot baths numbered H1 and H2, 31.80°C and 34.20°C in the warm bath (W1), and 30.00°C and 31.80°C in the warm bath (W2). The temperature distribution is more homogenous than the other scenarios with hypocaust system and observed temperature difference is not significant for this scenario.

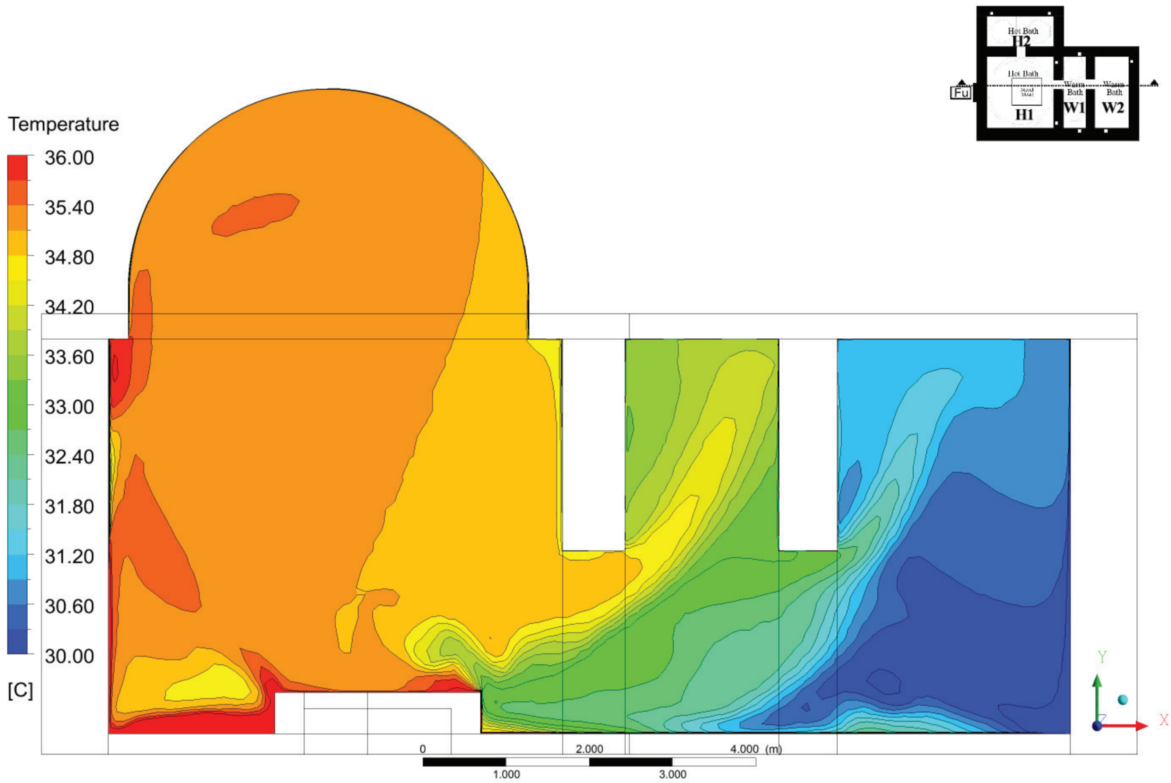

Figure 5.17. The temperature distribution in the x-y-plane.

Average air temperature of the warm bath (W2) is lower than the warm bath (W1) even for the same heat flux used at the bath. W1 behaves like a buffer zone between W2 and the hot bath (H1) and the air temperature changes gradually as can be seen in Figures 5.17 and 5.19.

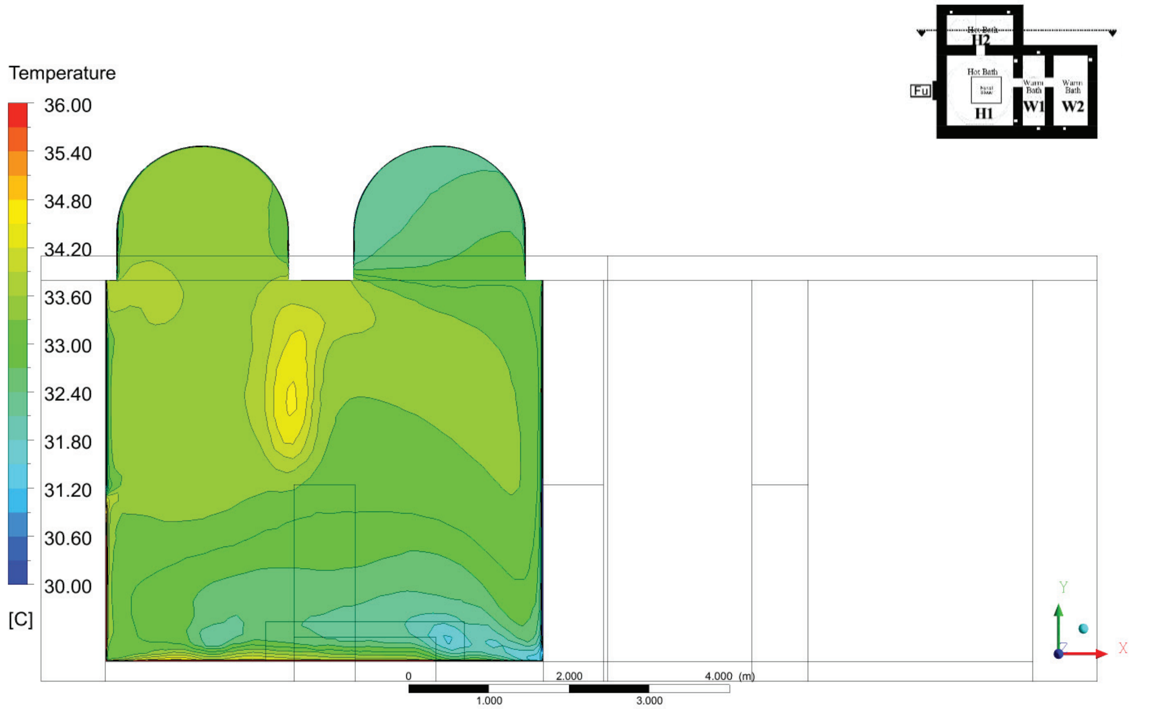

Figure 5.18. The temperature distribution in the x-y-plane.

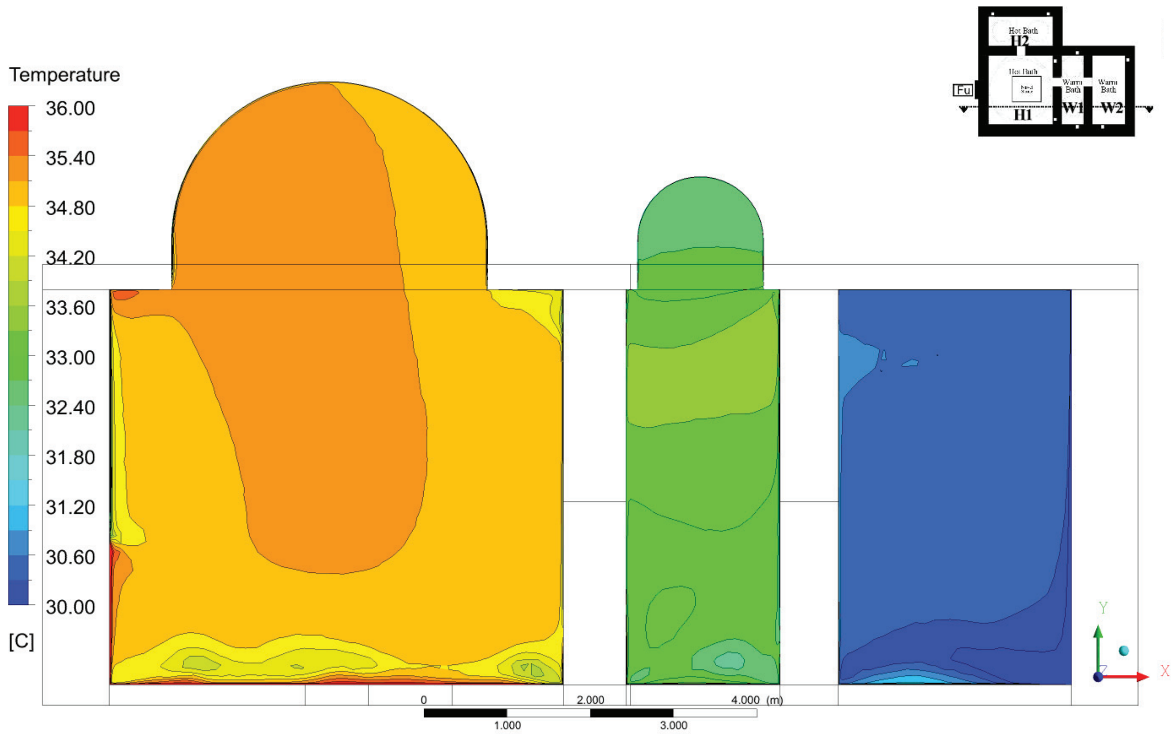

Figure 5.19. The temperature distribution in the x-y-plane.

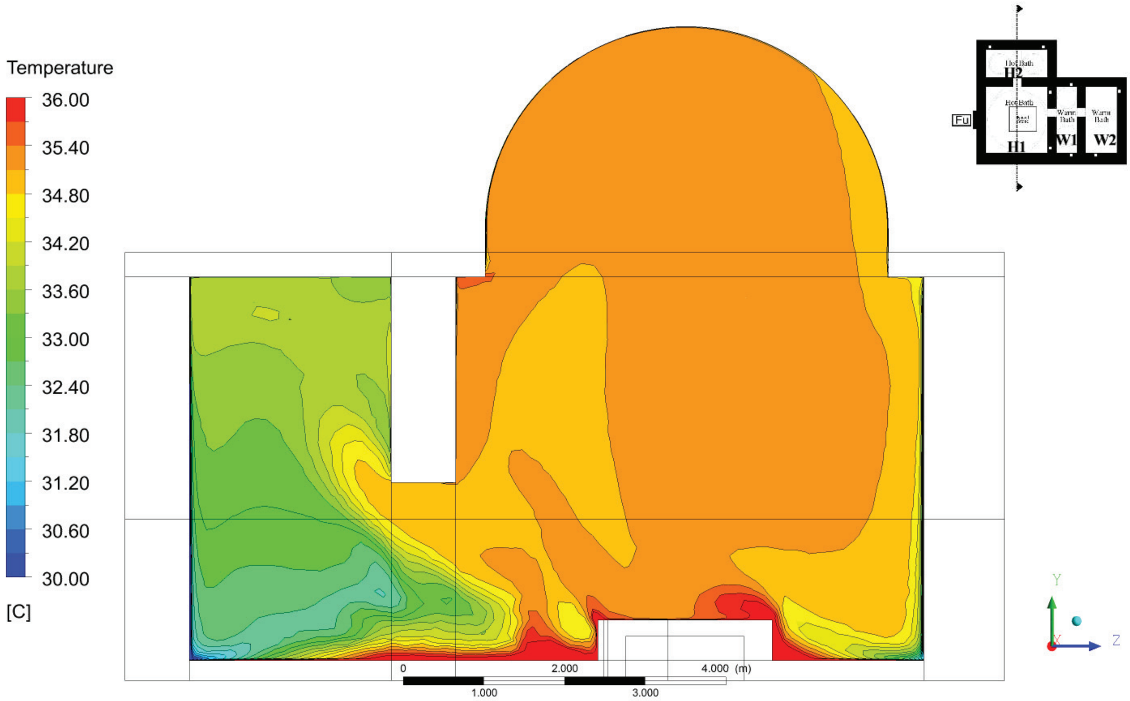

Figure 5.20. The temperature distribution in the xy-z-plane.

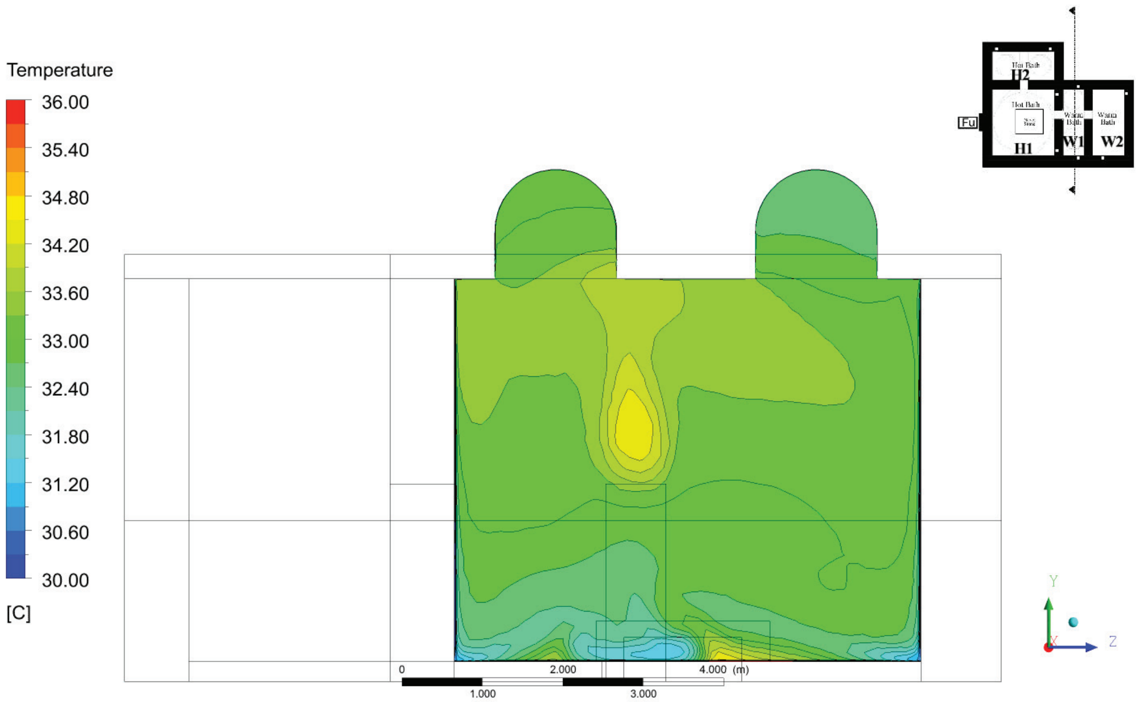

Figure 5.21. The temperature distribution in the y-z-plane.

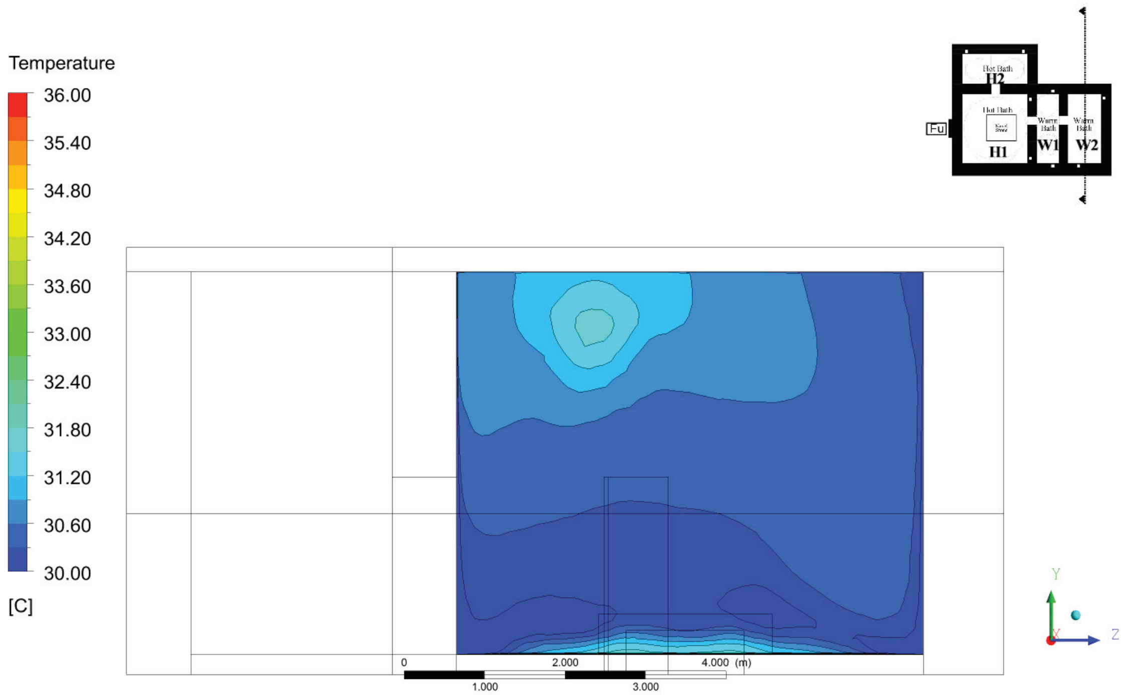

Figure 5.22. The temperature distribution in the y-z-plane.

The air temperature distribution at the cross-section of 1 m height is given graphically in the rooms of bath in Figure 5.23. In the biggest hot bath (H1), the temperature is approximately 35°C. This is the highest value compared to the other spaces because of the location of the pipe systems and relatively higher heat loss to the outside environment at the east wall of H2. At the other hot bath (H2), the average temperature is close to H1's average temperature value around 33°C. The lowest temperature value is around 30°C in this scenario which can be seen in the warm room numbered W2.

Temperature distribution of the floor surface of the bath is given in Figure 5.24. The figure shows that the temperature values are between 30°C and 40°C. These results can be defined by receive and return of pipes, pipe gaps and different heat flux values. Heat transfer rate from the floor surface to the bath sections is calculated as 2752.7 W totally, in this floor heating scenario.

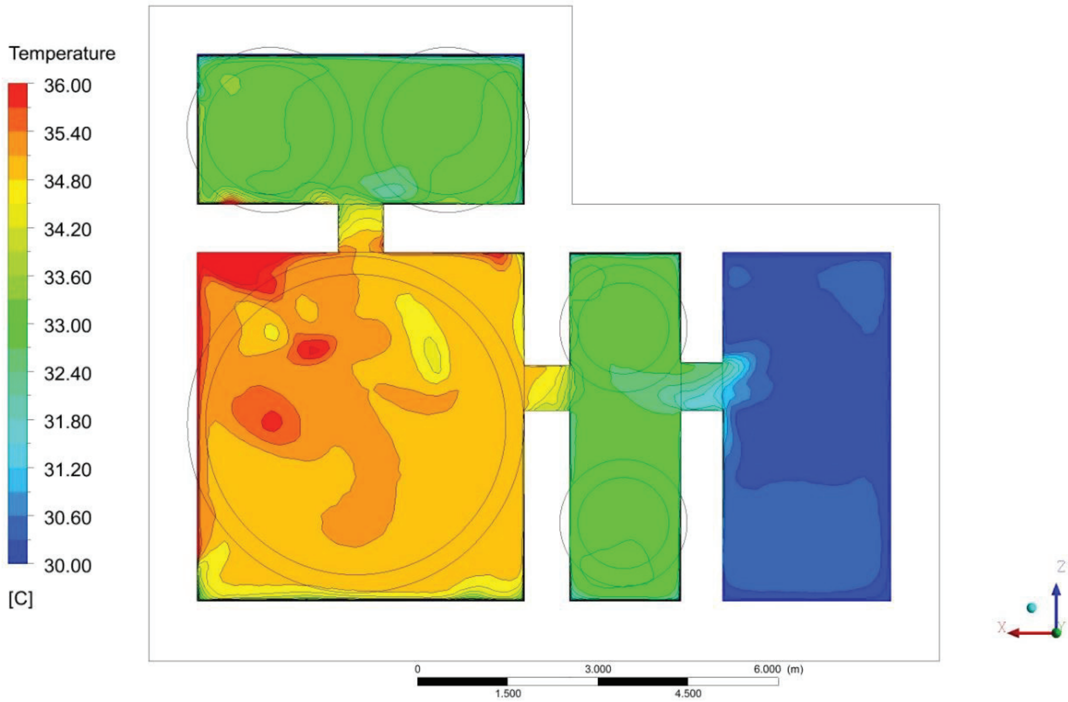

Figure 5.23. The temperature distribution in the x-z-plane at 1 m.

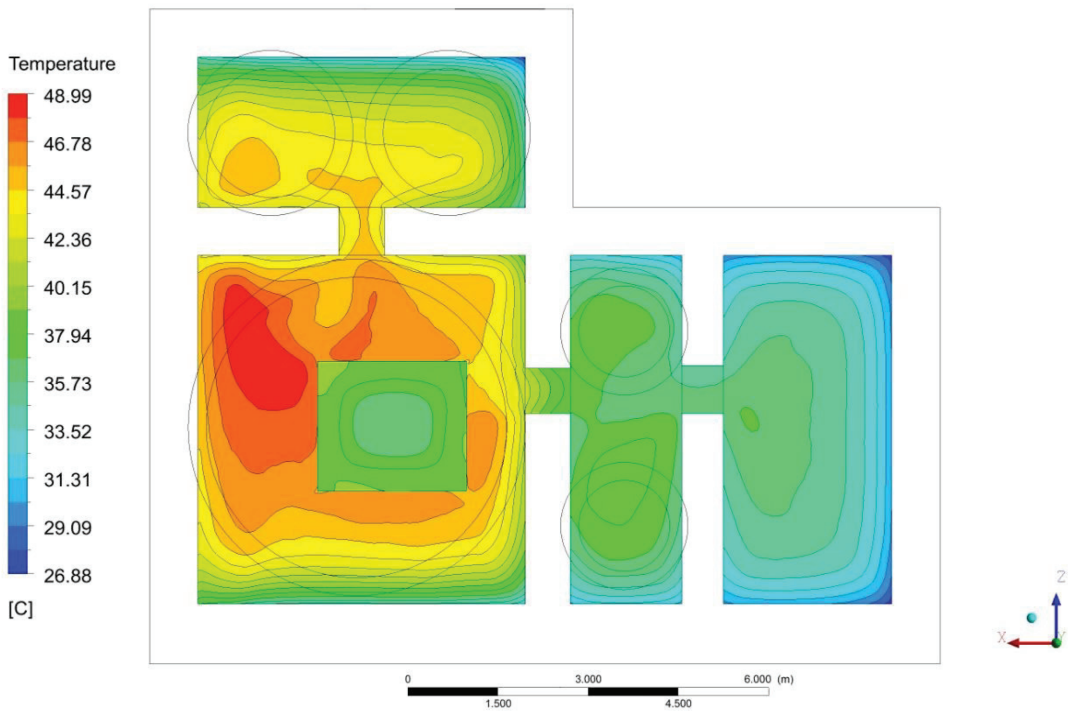

Figure 5.24. The temperature distribution on the floor.

Table 5.3. Temperature value in °C in hot baths (H1, H2) and warm baths (W1, W2).

	H1	H2	W1	W2
Scenario a Heating system with hypocaust	29.5 – 30.5	27.5 – 30.0	28.0 – 30.0	27.0 – 28.5
Scenario b Heating system with hypocaust	30.0 - 31.0	27.5 – 30.5	28.5 - 30.5	27.5 - 29.5
Scenario c Heating system with hypocaust	30.0 - 31.0	27.5 – 30.5	28.0 – 30.5	27.5 - 29.5
Scenario d Heating system with hypocaust	29.5 – 30.5	27.0 – 30.0	27.0 - 30.0	27.0 – 29.0
Floor Heating System	34.0 - 36.0	33.0 – 35.0	32.0 – 34.0	30.0 – 32.0

5.3. Discussion

The five cases were designed to research the heating system of the Alibey bath in the CFD simulation, four of them considered the traditional heating system with hypocaust and one of them considered floor heating system used nowadays. Firstly for hypocaust system with different chimney configuration cases flue gas exhaust were numerically analyzed by using ANSYS Fluent and the fluid flow and thermal condition of the bath were shown. After that, two heating systems from past to now were compared and significant results obtained from the 3D model. Velocity vectors and temperature distributions were obtained in the different sections of the spaces for each scenario. The amount of energy usage is defined in order to maintain thermal conditions on the bath.

In this study and other CFD studies in the literature, a wide range of results obtained based on the selected boundary conditions; such as choice of the mass flow rate and inlet temperature of the hypocaust system. According to the experimental studies of Kretzschmer [13] and Hüser [24], temperature values change depending on time and location. The flue gas temperature is very low at the further locations from the fire. The temperature value can be over 600°C at the fire region, but it may become less than 100°C at the inlet of the hypocaust system (Figure 5.25).

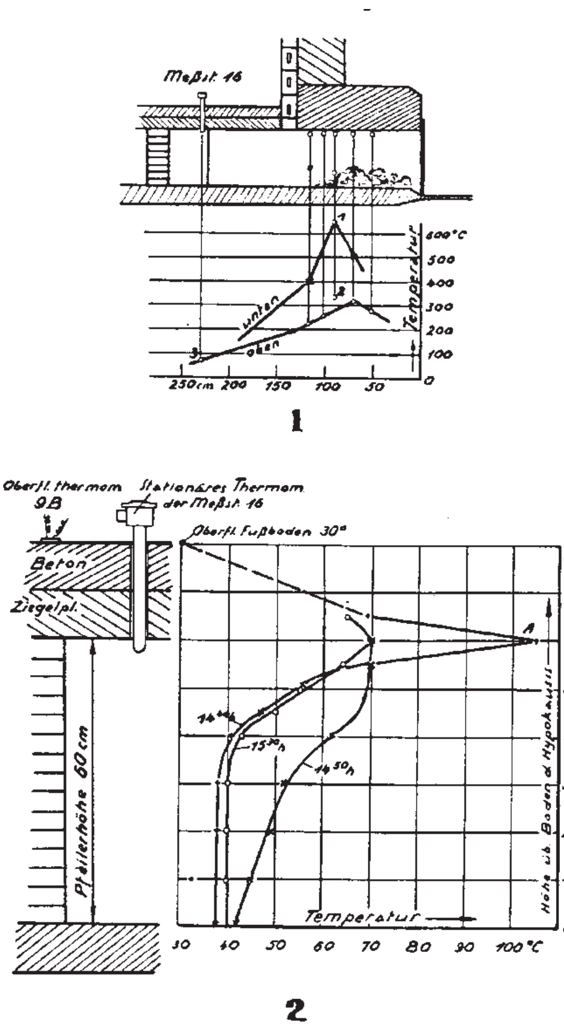

Figure 5.25. *Prafurnium* Temperature [13].

On the other hand, in the experimental study of Hüser [24], the hypocaust temperature values are related to the amount of fuel added to the furnace. Accordingly, temperature values change between 60°C and 120°C at the inlet of hypocaust system depending on added fuel. These values are between 40°C and 60°C two hours after fuel interruption, until the burning goes out (Figure 5.26).

These fuel rates and temperature values are indicative of time-related changes. Therefore, present study and the other CFD studies have variety of steady-state approaches and it is possible to obtain very different results with these numerical studies depending on numerical approaches.

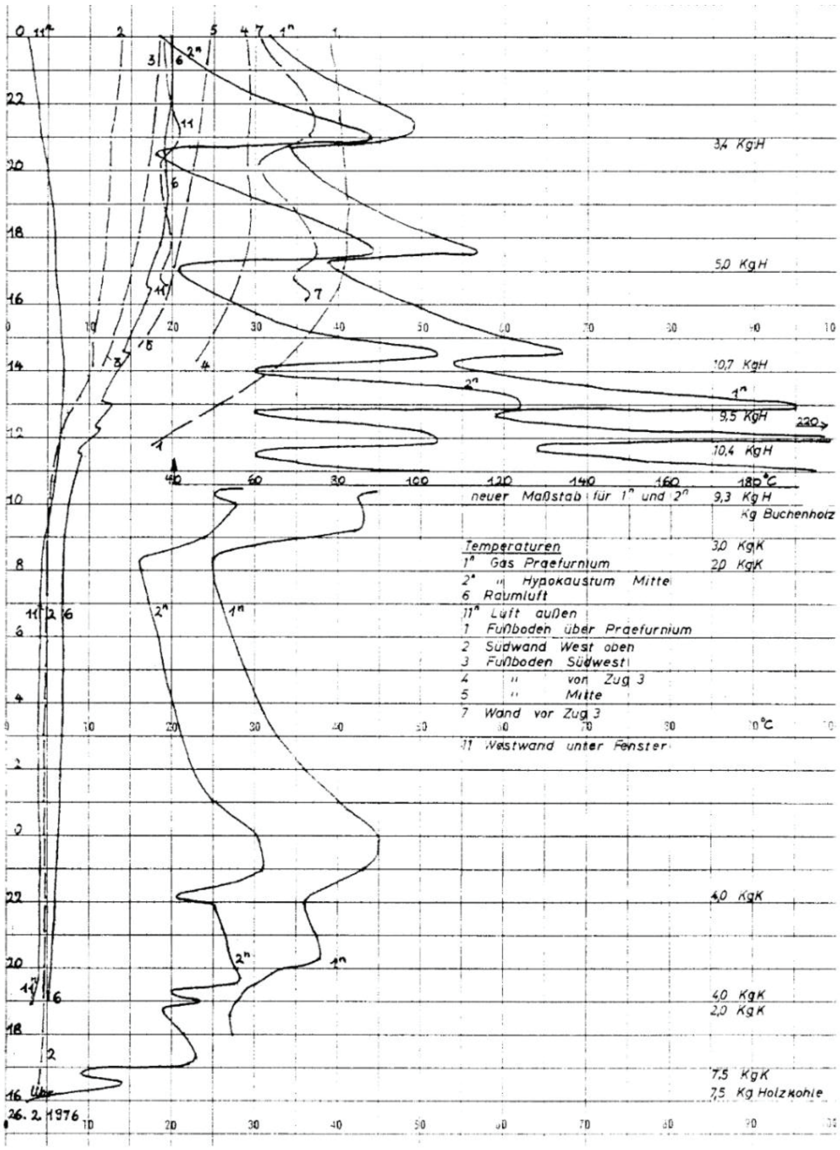

Figure 5.26. Temperature variation [24].

Several studies in the literature were evaluated considering heating systems in different climate conditions about traditional and under floor heating systems [13, 24-35]. These studies show that environmental conditions have a significant effect on the energy efficiency of the heating system: If the bath is used whole year, there are seasonal differences; hence the fuel consumption will change. Fuel consumptions will also change depending on the bath dimensions.

The heat transfer rate from the floor surface of the Alibey Bath is approximately between 1170 W and 1240 W which is obtained from different operating conditions, for the four different cases of the traditional heating system of the bath. On the other hand, the energy rate of the hypocaust system is 11,191 W which corresponds to about %11 system efficiency. In addition to this, the average heat flux value from the surface of the bath, is calculated as about 16 W/m^2. However, the average heat flux rates are chosen as 30 W/m^2 and 60 W/m^2 for hot and warm bath, respectively, in the floor heating system with hot water circulation. According to this, the total heat transfer rate is calculated as 3601.5 W for heating sections, while this value is calculated as 2752.7 W in CFD simulation. Heat flux input value is calculated as average 37.2 W/m^2 for all heated surfaces in the floor heating system. After numerical results, air temperature value difference is about 4°C in the Alibey bath, between traditional and the floor heating systems. As a result of this 4°C difference, the air temperature in the heated rooms is approximately close to desired air temperature of the bath in the floor heating system. It should be noted that in the hot water boiler the energy obtained from the burning of wood shaving needs to be higher. The required energy rate input is calculated as approximately 5145 W for hot water boiler with an assumption of %70 efficiency. In this case, floor heating system has a total efficiency of %53.5. The heat fluxes values in the traditional and floor heating systems are calculated, based on an outdoor temperature of 8.8°C [40]. In contrast, outdoor design temperature value should be taken as less than 8.8°C. Accordingly, the heat flux value should be about 100 W/m^2.

Surface temperature homogeneity is an important parameter on the thermal design of the baths (e.g. differences at the surface temperature of the same bath is not a desired condition for baths). As the floor heating system provides more homogeneous temperature distribution at the floor surface than the hypocaust system, it allows a better thermal condition for the baths. Additionally, the floor heating systems are much more economical than hypocaust systems. For this reason, floor heating system becomes prevalent to the other heating system.

Based on these results, heating systems with hypocaust has more heat loss, hence require more fuel consumption. Additionally, in the winter months more fuel consumption will be necessary in order to provide desired indoor temperature. It can be concluded that many trees may have been cut to meet the amount of wood required for hypocaust systems. On the other hand, the heat storage capacity of the walls, the changing outside environment under the unsteady real conditions, flue gas radiation, and indoor moisture level are also effective parameters and should be considered as the variables on the thermal calculations. The flow of flue gas is a complex problem in the hypocaust system that requires detailed modeling and experimental work. Thus, results may include some errors because of the fact that calculations based on aforementioned assumptions.

CHAPTER 6

CONCLUSION

The aim of the study is to compare and evaluate the heating systems of Turkish bath from past to present. For that purpose, Alibey bath is chosen as a case study. Heated rooms of the Alibey bath are modeled in the CFD environment by the original hypocaust heating system with different chimney configurations and the modern under floor heating system with circulated hot water. These traditional and modern systems are compared with each other under the consideration of energy efficiency and the conservation improvement solutions.

At the first stage, a survey research is carried out to create a 3D virtual model in the ANSYS Fluent program under the specified boundary conditions and to make preliminary assumptions about the original heating system and the configuration of the chimney position in the bath. At the second stage, a 3D simulation model is created and the boundary conditions are defined about the floor heating system for the purpose of comparing original heating system and floor heating system of the bath. The CFD simulation results after running the program for different scenarios are used for providing realistic information on the temperature distribution of the different sections of the bath, velocity distribution of the flue gas and air inside of heated bath sections. The heat transfer rates with fuel consumptions are also investigated for different working conditions. Totally five different scenarios are characterized by the original heating system with the configuration of chimney position and the floor heating system are numerically analyzed.

Under the condition of outdoor temperature assumed to be 8.8°C which is the average value of January as a coldest month, the indoor average temperature was found as around 30°C in the hot rooms so long as the flue gas outlet temperature from the furnace which is also inlet temperature of the hypocaust system is defined as 90°C. On the other hand, under the same outdoor conditions, the indoor average temperature was found approximately 34°C for under floor heating system circulating hot water.

For comparison to the chimney position configuration for the hypocaust heating system scenario b gives the highest heat transfer value to the heated rooms and creates more homogenous temperature distribution at the floor surfaces of the heated rooms individually. The reason for that is more effective chimney configuration which the flue gas releases sufficient amount of hot gas for each chimney. Thus, flue gas can reach every place of the hypocaust system. Although the temperature distribution is close to each other for each scenario; but in the scenario b, the temperature distribution values are approximately greater than 1°C. In contrast to this, the temperature distribution is much more homogenous in the 3D model of the floor with hot water circulating heating system and the values are 4°C greater than the other scenarios. For this temperature difference, a more heat transfer rate input is required at the floor heating system. Thus, a more favorable result is obtained for the desired bath conditions. The efficiency values of the system are also examined and the traditional heating system was %11, while the new system was higher than %50.

According to results, if the spaces are heated by hypocaust system, excessive amount of wood burning is necessary to reduce heat loss. Moreover, when the temperature is very low in a day of the winter months, much more fuel consumption will be required to reach the desired indoor temperature.

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