Comparative Study of Form and Features of Courtyards in Terms of Outdoor Thermal Comfort in Two Contrasting Climates of Iran

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Abstract

Courtyards as a traditional strategy were used to create a suitable microclimate for dwellers, but in contemporary architecture, inadequate knowledge of form and features of courtyards makes them deficient. This study presents practical solutions reaching optimal form and features of courtyards based on the traditional architecture of two contrasting climates of Iran. The ENVI-met.4 model was used for simulating the area percentage, water and vegetation level in a very cold climate of Ardabil and Hot-arid climate of Yazd. The simulated atmospheric parameters were imported to the Rayman1.2 to calculate PET thermal index. As the first step, 10% of the total area was advised to be considered a courtyard area for Yazd hot-arid climate, and 60% of the total area was recommended in a very cold climate of Ardabil. Next, the ratio of the water area to the total area of courtyards was simulated and the results advice, 0% of the courtyard to be considered a water area of Ardabil and 10% of the courtyard of Yazd is an optimum choice in hot-arid climate. In the final step, 20% of courtyards recommended the best condition of tree coverage in both climates. By these guidelines, designers can create a more adaptive architecture to the local climate.

Keywords: outdoor thermal comfort, courtyards, microclimate, contrasting climates, ENVI-met4

1. Introduction

Open spaces usually cover more than two-thirds of the urban area in modern architecture; thus their microclimate dominates the urban canopy layer (UCL) climate. (Shashua-Bar & Hoffman, 2004).

Perfecting the thermal environment of buildings and their surrounding outdoor environment is a multidisciplinary necessity to create an urban microclimate and achieving outdoor thermal comfort (Berkovic et al., 2012; Wong et al., 2003; Saito et al., 1990; Wong et al., 2011).

Currently, in city development, the Urban Heat Island phenomenon is increasing and the effects of UHI on human health, energy consumption and air quality are considered by researchers. However, architectural tools and forms can play a part in mitigating the effects of UHI, and also in the climatic effect on human comfort levels. (Taleghani et al., 2015; Ali-Toudert et al., 2006; Ahmed, 2003; Johansson, 2006).

Developing an understanding of suitable forms and materials can radically help to adopt thermal environment in outdoor settings, and thus reduce energy consumption in indoor conditions. The courtyard concept is a common and ancient method in architectural design, especially in Middle Eastern countries like Iran. (Edwards, 2006). The advantages of the courtyard and its thermal characteristics have been evaluated by some studies in different climates, both in measurement and computer modeling methods. (Safarzadeh et al., 2005; Taleghani et al., 2014; Aldawoud & Clark, 2008; Zhai & Previtali, 2010; Yao & Steemers, 2013).

There are some studies of courtyard thermal features in the tropical climate (Makaremi et al., 2012; Fahmy & Sharples, 2009; Rajapaksha et al., 2003; Sadafi et al., 2011) but Iran's courtyards feature in a wide range of different climates, so they warrant detailed investigation. Analogous application of courtyard form, material, and vegetation might cause a malfunction in the performance of courtyards in different climates of Iran. This study aims to evaluate quantitatively the comfort condition of the courtyards in two different climates of Iran in terms

of dimension, vegetation, and water level. This study is being carried out in order to develop guidelines for creating more sustainable environments in these climates.

2. Material and Methods

2.1 Simulation Software and Thermal Index

The thermal performance features of the courtyards were analyzed based on the following design parameters: the dimension, vegetation, and water. These parameters are selected based on the real examples of the courtyard features in Iran. These 3 parameters are the most important issues in courtyard planning. It should be noted that there is enough research about other parameters (like albedo of the materials and the height and wall enclosure), and the results of the simulation are predictable. For example; materials with high albedo make outdoor conditions, more and more exposed to high radiation, and also SVF has an effect on the comfort condition. The result of these studies proved that shaded places have a better condition in terms of thermal comfort (Taleghani et al., 2015; Makaremi et al., 2012; Ghaffarianhoseini et al., 2015).

So analyzing and simulating the local and practical parameters for local courtyards is a fundamental issue. ENVI-met 4, a three-dimensional fluid dynamics microclimate software, was used to simulate the outdoor thermal condition of the courtyards. With Version 4.0 the microclimate simulation ENVI-met takes a huge step forward in terms of the accuracy and realism of the simulations. Due to the new 3D format, there are no longer any limits to the architecturally detailed reproduction of the model area.

The new features of the ENVI-met 4 are mentioned according to the following items:

3: Forcing (Huttner, &Bruse, 2009).

(i) Full 3D editor

(ii) Advanced calculation of façade temperature and wall energy balance**.**

(iii) Forcing (Huttner, &Bruse, 2009).

One of the most important features of ENVi-met software is its capability to generate the accurate Tmrt for the outdoor condition (Huttner et al., 2008; Chow &Brazel, 2012) and to calculate the Physiological Equivalent Temperature (PET).

Table 1. PET thermal comfort category (Hoppe, 1999)

PET°C	Thermal Perception	A grade of physiological stress
Below+4	Very cold	Extreme cold stress
4 to 8	Cold	Strong cold stress
8 to 13	Cool	Moderate cold stress
13 to 18	Slightly cool	Slight cold stress
18 to 23	Comfortable	No thermal stress
23 to 29	Slightly warm	Slight heat stress
29 to 35	Warm	Moderate heat stress
34 to 41	Hot	Strong heat stress
41<	Very hot	Extreme heat stress

2.2 Study Area

A simulation method was employed for analyzing the thermal effect of courtyards in Ardabil and Yazd, Iran. These two cities in Iran have completely different climates. Ardabil (48°18'E. Long, 38°15'N. lat) is located in the northwest of Iran and it has a very cold climate. Because of its rash, cold climate, designing the outdoor spaces in this city has some limits and specific principles. There is an impact of the cold wind and solar radiation, humidity, etc. (Jalilian & Tahbaz, 2006; Namin & Khoshvalad, 2015). Yazd (55°0'E. long, 32°0'N. lat) is situated in the center of Iran. This city has a hot and arid climate. Outdoor spaces in this region need special attention to possible ventilation and solar radiation (Hedari, 2010; Teimourtash, 2013). A very cold and long winter is one of the most significant features of the Ardabil climate. In table 1, the long-term climatic data of Ardabil are presented for the 1976 to 2010 period, and also the Physiological Equivalent Temperature (PET) is calculated.

The calculations of PET are done via Rayman for a normal 35-year-old male person of 1.75 m high and 75 kg, with a metabolic rate of 80 Watt (the Rayman default parameters). An activity level of 80 W arises when a normal person is walking with 1.2 m/s. PET frequency is presented in Fig1.

Table 2. Longtime meteorological data of Ardabil (1976-2010) (chaharmahalmet. ir, 2016)

	T_a(Min)	T_a(Max)	T_a (Mean)	RH% (Min)	RH% (Max)	RH% (Mean)	Wind Dir	Wind Speed m/s	PET
JAN	-7.8	3.0	-2.4	61	87	75	225	18.0	-9.7
FEB	-5.8	4.9	-0.5	58	88	74	225	17.5	-7.2
MAR	-2.0	9.8	3.9	53	89	73	90	13.1	-1.4
APR	2.9	16.6	9.7	46	88	68	90	13.3	4.9
MAY	6.2	19.9	13.1	50	91	71	90	13.4	8.5
JUNE	9.2	23.4	16.3	50	91	71	90	14.2	12.1
JULY	11.7	25.1	18.4	51	88	69	90	15.1	14.3
AUG	11.7	25.1	18.4	51	88	70	90	14.5	14.5
SEP	8.9	22.7	15.8	51	92	74	90	13.7	11.8
OCT	5.1	17.7	11.4	54	92	75	90	13.0	7.1
NOV	0.3	11.6	5.9	55	90	74	225	16.5	0.3
DEC	-4.5	5.9	0.7	59	88	74	225	17.4	-5.8

The rough cold climate of Ardabil can be understood from table 1, so in this paper; the coldest day of the Ardabil is chosen for the simulation and the calculated data. In contrast, the hot and arid climate of Yazd - with its long-term climatic data - is introduced in table 2. This data is for the period spanning from 1976-2010. The PET value is calculated via Ray man model. Long-term PET frequency of Yazd is presented in Fig2. The differences of the climate data in these cities definitely point to the need for different principles in architecture and urban planning.

Table3. Longtime meteorological data of Yazd (1976-2010) (chaharmahalmet.ir, 2016)

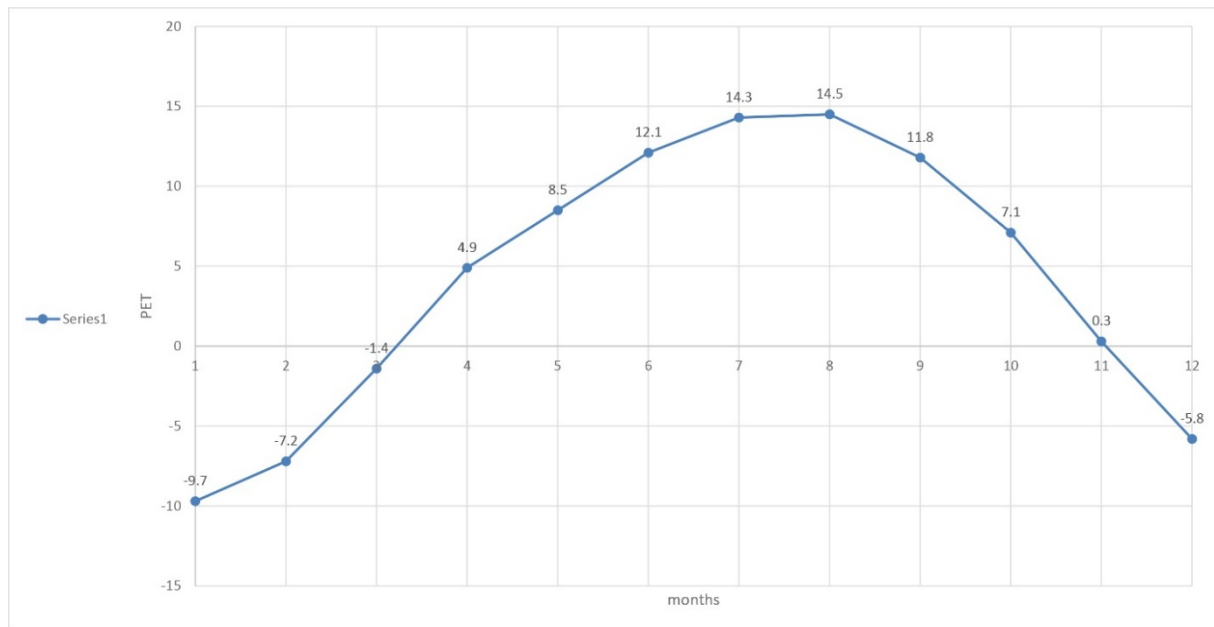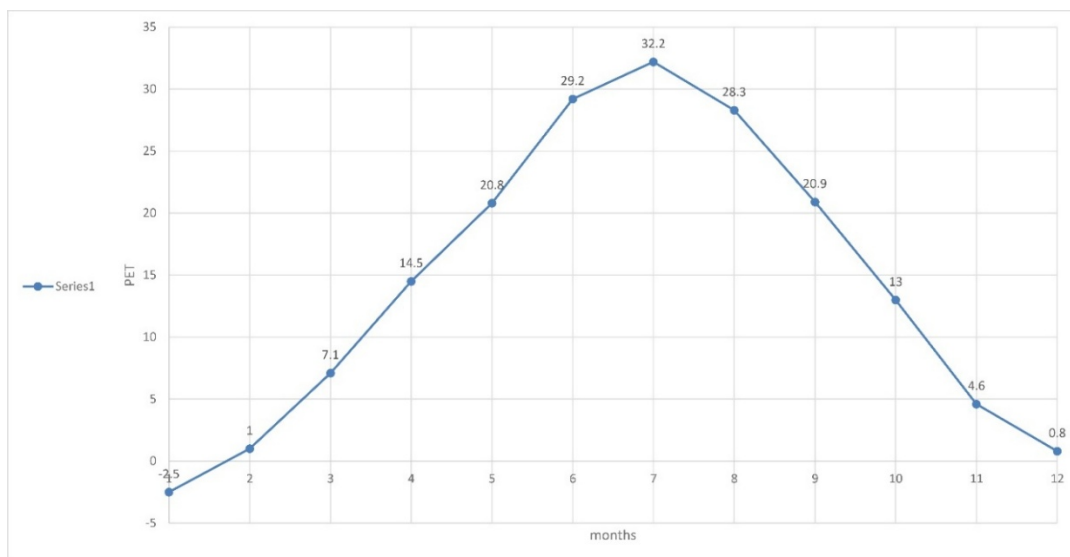|	T_a(Min)	T_a(Max)	T_a (Mean)	RH% (Min)	RH% (Max)	RH% (Mean)	Wind Dir	Wind Speed m/s	PET
JAN	-0.4	12.3	5.9	35	73	54	135	6.6	-2.5
FEB	2.1	15.7	8.9	26	65	44	270	8.1	1.00
MAR	6.9	20.6	13.7	21	57	37	270	8.8	7.1
APR	12.5	26.6	19.6	19	50	32	270	9.2	14.5
MAY	17.6	32.3	24.9	15	39	25	315	9.7	20.8
JUNE	22.4	37.8	30.1	12	27	18	315	9.0	29.2
JULY	24.5	39.5	32.0	11	26	17	315	9.2	32.2
AUG	22.0	38.0	30.0	11	26	17	315	8.5	28.3
SEP	17.6	34.3	25.9	12	28	19	315	7.9	20.9
OCT	11.5	27.7	19.6	14	39	27	270	7.0	13
NOV	5.1	20.0	12.5	24	55	38	135	5.8	4.6
DEC	0.7	14.3	7.5	32	68	50	135	6.4	-0.8

Figure 1. Long-term PET frequency(1976-2010)

Figure 2. Long-term PET frequency (1967-2010)

2.3 Selection of Typical Days

Based on available information about the climate of Iran, and according to the meteorological report of Ardabil, the annual mean air temperature of the city is 9.22°C and the mean relative humidity is72.33%. The East wind (90°) is a prevailing local wind with 14.975 m/s wind speed. Based on Ardabil meteorological organization reports, February, 2nd of 1989 was the coldest day in Ardabil with -33.8 °C of air temperature (Ardabilmet, 2016).

Accordingly, Yazd meteorological organization reports show that annual mean air temperature of Yazd is 19.21°C and mean relative humidity is 31.5, and also the wind velocity is 8.016m/s with northwest (315°) prevailing direction. According to the Yazd meteorological organization reports, 13 July 2012 was the hottest day in Yazd with an air temperature of 45.6°C. (Yazdmet, 2016). With this information, the thermal features of the two different climates of Iran will simulate in terms of better thermal comfort condition. The input data for

simulation is presented in table4.

Table 4. Conditions used in the simulations with ENVI-met 4.

Simulation parameters	Ardabil	Yazd
Simulation day	02.02.1989	13.07.2012
Simulation period	11h(7:00-18:00)	14h(6:00-20:00)
Spatial resolution	1m horizontally,2m vertically	1m horizontally,2m vertically
Initial Temperature	239.35	302.15
Wind speed	3m/s	2
Wind direction (N=0,E=90)	90	135
Relative humidity(in 2m)	100%	23%
Indoor temperature	300K(27°C)	293(20°C)
Initial Temperature Upper Layer (0-20 cm)	239	302.15
Initial Temperature Middle Layer (20-50 cm)	232.15	300
Initial Temperature Deep Layer (below 50 cm)	229.4	297.15
Relative Humidity Upper Layer (0-20 cm)	100	23
Relative Humidity Middle Layer (20-50 cm)	100	25
Relative Humidity Deep Layer (below 50 cm)	100	28
Adjustment factor for solar radiation	1	1
clouds	Default	Default
Turbulence model	Use default values	Use default values
LBC	For Ta,RH:Open,turbulence;forced	For Ta,RH:Open,turbulence;forced

3. Literature Review

3.1 Thermal Comfort Analyses of Courtyards

Courtyards are enclosed or semi-closed, open spaces housed in building environments, especially in the context of traditional architecture, which use vegetation and water to provide thermal comfort and to suit the microclimate to its inhabitants. Courtyard concept is a common method of local house designing in the Middle East, especially in Iran. (Almhafdy et al., 2013; Costello, 1977; Mirmoghtadaee, 2009; Ghaffarianhoseini et al., 2015).

The main function of courtyards in all countries is to modify the effect of climatic parameters on inhabitants and to create a suitable microclimate based on local climate. In different climates, different strategies are used to modify the rough environment. (Aldawoud, 2008). A courtyard concept with different features based on the local climate is one of the main principles of vernacular architecture (Coch, 1998). For example, the use of passive ventilation to avoid the annoying humidity in tropical and humid areas is the most significant feature of courtyards in these regions. (Rajapaksha et al., 2003; Sadafi et al., 2011; Makaremi et al., 2012). In hot and arid regions, modification of the environment by water, vegetation, etc., is the most common solution to modify the climatic parameters. (Etzion, 1990; Attia, 2006; Al-Hemiddi et al., 2001). Cold climates also have their own features to avoid annoying wind and to reach sun rays. (Shokouhian et al., 2007; Song et al., 2015; Zhang et al.,

2015).

The courtyard concept plays an important role in designing various public facilities such as education, residential areas, and healthcare facilities, but there are not enough strategies to enhance the thermal comfort of courtyards in the different climates of Iran. Uniform design of courtyards in diverse climates of Iran has caused lots of problems in terms of thermal comfort. Lack of sufficient knowledge of thermal characteristics of the courtyards is the main reason for this problem. Courtyards are mostly analyzed in terms of their airflow, solar radiation, and shadow features.

The ventilation potential of the courtyards and their effect on the thermal comfort has been evaluated by CFD studies and wind tunnels in various climates. (Mousli & Semprini, 2015; Almhafdy et al., 2015; Jamaludin et al., 2014). Shade and its effect on the thermal comfort in courtyards are reported as being an important issue in developing the comfort range and energy consumption. (Meir et al., 1995; Yaşa & Ok, 2014). Energy performance of courtyards has been investigated by many researchers (Aldawoud& Clark, 2008; Muhaisen & Gadi, 2006; Manioğlu & Yılmaz, 2008; Dunham, 1961; Al-Masri & Abu-Hijleh, 2012; Behbood et al, m2010; Safarzadeh & Bahadori, 2005). Aldawoud et al discussed the energy performance of the courtyard and of atrium-based buildings. They proved that in general, the open courtyard shows a better energy performance for lower buildings. As building height increases, however, at some point, the enclosed atrium exhibits a better energy performance than the courtyard. With atrium research, some case studies depend on other factors such as glazing and climatic parameters. (Aldawoud & Clark, 2008).

Courtyard proportions and their effect on heat gain and energy requirement were investigated in a Rome climate by Ahmed & Muhaisen. The study, consequently showed that the proportions of the building that houses the courtyard considerably influence the need for heating and cooling. (Muhaisen & Gadi, 2006). In the hot and arid climate of Iran, Behbood et al showed that courtyard method is one of the efficient strategies in terms of energy consumption (Behbood et al., 2010).

In another example of Iranian courtyard research, the passive cooling of courtyards has been investigated by the Safarzadeh et al, and they showed that a courtyard alone cannot make thermal comfort in Tehran, Iran but it can decrease the cooling energy load (Safarzadeh & Bahadori, 2005). Hedari, in his Ph.D. thesis, investigated the thermal comfort in the courtyards of Ilam, Iran. The findings of the study revealed that the people in Ilam could achieve comfort at higher indoor air temperatures compared to the recommendations by international standards like ISO 7730. The results also showed that passive systems such as the main comfort strategy could be applied to housing design in Ilam. By using the results of this study, strategies to minimize energy consumption, not only for Ilam but also for other regions, which have similar climates and cultures to Ilam, can be proposed. (Heidari, 2000).

Taban et al tried to get an optimal courtyard pattern in Dezful by local shadow analysis, and they revealed that courtyards with a length/width ratio of 1 to 1.4 (near to square form) and height/length ratio of 1.1 to 1.2 had the most proper shade on different courtyard surfaces. Results also showed that for the purpose of reducing the cooling load in summer, deep and square-shaped courtyard forms were the most preferable. The self-shading of the courtyard building acts to reduce the need for cooling by an average of about 4%. By using this proportion, the amount of shadows on the courtyard will be optimized (Taban et al., 2014). Modelling study showed that the effect of rectangular courtyard proportions on the shading and exposure conditions produced on the internal envelope of the form in four different locations in Kuala Lumpur, Cairo, Rome and Stockholm and the results showed that the shading conditions of the courtyard internal envelopes are significantly dependent on the form's proportions, location latitude, and available climatic conditions. (Muhaisen, 2006).

A study by Taleghani et al, analyzed the energy performance and thermal comfort of the Netherlands with the light climate changes of this country. The results of this research, which analyzed monthly energy performance, comfort hours and climate scenarios, indicated that using an open courtyard from May through October and an atrium, i.e. a covered courtyard, in the rest of the year establishes an optimum balance between energy use and summer comfort for the severest climate scenario. (Taleghani et al., 2014).

Al-Masri et al, evaluated the courtyard housing in mid-rise buildings of Dubai, United Arab Emirates. In this study, the courtyards have been assessed in terms of energy consumption and daylight factors, and the result of this study shows that the energy consumption of the optimal courtyard is 11.16% less than conventional form building and about the daylight factor. In the courtyard form in both winter and summer time, the courtyard has a better thermal condition. (Al-Masri et al., 2012). The effect of a courtyard's shape and geometry on heat gain and energy efficiency in various climates has been assessed by Yaşa& Ok. In this study, the optimal shape of the courtyard was presented by CFD Fluent (Yaşa & Ok, 2014).

Climatic variables and their effect on thermal comfort are discussed by Sthapak & Bandyopadhyay. In this study, in addition to the placement of the rooms and the proportion of the openings, the degree of enclosure of the courtyards and also the breeze and shadow effect on thermal comfort - especially in light time - are scrutinized. (Sthapak & Bandyopadhyay, 2014). Because of the diverse climate of Iran, new bioclimatic research has been done by Pourvahidi & Ozdeniz. In this study, the bioclimatic conditions of Iranian cities were determined and as a result; five climates were identified in Iran.

In order to prove that this new classification is valid, the traditional architecture of these regions was juxtaposed. It turned out that the traditional buildings have different features in these five regions. (Pourvahidi&Ozdeniz, 2013). A study of the environmental effect of the residential building courtyards in different climates was done by Taleghani et al, The findings of these studies show that the different configurations of courtyard buildings, such as natural elements, and the situation of openings in different facades are the most important findings of this review paper. (Taleghani et al., 2012).

Recently some studies have examined the comfort condition of the courtyards as a house and urban forms (Ghaffarianhoseini et al., 2015; Taleghani et al., 2015; Berkovic et al., 2012; Taleghani et al., 2014). Comfort condition of the courtyards is simulated by ENVI-met model software using the PMV thermal index and in this study, Berkovic et al presented the design guidelines for courtyards in Israel and compared various courtyard geometries and shading using trees, openings, and galleries (Berkovic et al., 2012). Cooling strategies of Netherlands courtyard were investigated by a parametric study, and results of this paper demonstrate three heat mitigation strategies for the urban courtyard. ENVI-met was validated for the Netherlands with measurement. (Taleghani et al., 2014).

In another study of the thermal characteristic of the courtyard in a hot and humid climate of Tainan, Taiwan, by Yang et al, the results of this study showed that the integrated design approach can effectively reduce the frequency of heat stress from 79.7% to 40.5% and it is noticeable that by this study, the potential and limitations of the ENVI-met model, is applied in tropical climates (Yang et al., 2016). Thermal assessment of the Portland university courtyard is done by Taleghani et al, in this study, heat mitigation strategies in this university were examined by ENVI-met model and the results showed that the maximum PCI effect was 5.8 °C between a park and a parking lot. Vegetation and a water pond reduced 1.6 °C and 1.1 °C Ta for a bare courtyard, and finally, high albedo material increased Tmrt but reduced Ta. (Taleghani et al, 2014). The study by Ghaffarianhoseini et al, tries to represent the optimal forms of the courtyard in Malaysia. These courtyards have been examined by four parameters of orientation, vegetation, albedo, and height. Consequently, they have evaluated the optimal choice of these parameters represented by ENVI-met simulation for the Malaysian courtyards (Ghaffarianhoseini et al., 2015). Taleghani et al examined the five urban forms of the Netherlands and the final results show that the courtyard form is the best form in terms of PET, Tmrt,… in the moderate climate of the Netherlands (Taleghani et al., 2015).

3.2 Calculation of PET as Thermal Comfort Index

The physiological equivalent temperature, PET, is a thermal index derived from the human energy balance. It is well suited to the evaluation of the thermal component of different climates, as well as having a detailed physiological basis (Prata-Shimomura et al., 2009).

The PET index is often used in environmental comfort research for analyzing the physiological behavior of users and pedestrians, according to environmental conditions (effect of buildings and climate). (Matzarakis et al., 1999). PET as thermal comfort has been used in several studies of outdoor thermal comfort (Thorsoson et al., 2007; Andrade & Alcoforado, 2007; Oliveria & Andrade, 2007; Johansson, 2006; Emmanuel & Johansson, 2006) because the PET index has been primarily designed for outdoor use (Spagnolo & Dear RJ, 2003). PET can be calculated using free software (Rayman). This software is validated software for urban complex shading (Lin et al., 2006; Gulyas et al, 2006; Matzaraki et al., 2007). Environmental data for the PET calculation that is required in the Rayman model includes air temperature (T_a), relative humidity (RH%), wind velocity (v), mean radiant temperature (Tmrt) and vapor pressure (VP) and personal data such as human clothing and activity and local data such as the date of year, time and location. Comfort classification of PET scale is described by below table 1.

4. Results and Discussion

4.1 Reliability of ENVI-met4

In this step, ENVI-met model (the courtyard shape as a sample) was validated through a comparison between field measurements and simulation results. The measurements were done in a courtyard building representing a traditional house of Ardabil and Yazd. Manafzadeh house in Ardabil and German house in Yazd were selected to

assess the reliability and calibration of ENVI-met4. For this assessment, two different days in two different climates of Iran were selected. The air temperature sensor was protected by a white shield to minimize the effect of the radiation. The courtyards' environments were measured for 11 days in February for Ardabil and June for Yazd.

Among these 11 days, two days for each city were selected randomly for Envi-met simulation. February 5th and 13th of 2015 and June 15th and 23rd of 2015 were the random days. The weather data for the simulation process were taken from the local weather station. The data from simulations and measurements are compared to show the accuracy of the simulation results. To do this simulation, an Envimet Area input file and configuration files are needed. The input-file are described in table 5 and 6.

Table 5. Ardabil configuration data for ENVI-met4 validation

Simulation parameters	Ardabil	Ardabil
Simulation day	05.02.2015	13.02.2015
Simulation period	24h(21:00-21:00)	24h(21:00-21:00)
Spatial resolution	1m horizontally,2m vertically	1m horizontally,2m vertically
Initial Temperature	273.15	272.15
Wind speed	3m/s	9m/s
Wind direction (N=0,E=90)	45	225
Relative humidity(in 2m)	100%	100%
Indoor temperature	300K(27°C)	300K(27°C)
Initial Temperature Upper Layer (0-20 cm)	273.15	272.15
Initial Temperature Middle Layer (20-50 cm)	269.45	269.45
Initial Temperature Deep Layer (below 50 cm)	265.15	264.15
Relative Humidity Upper Layer (0-20 cm)	100	100
Relative Humidity Middle Layer (20-50 cm)	100	100
Relative Humidity Deep Layer (below 50 cm)	100	100
Adjustment factor for solar radiation	1	1
clouds	Default	Default
Turbulence model	Use default values	Use default values
`LBC	For Ta,RH:Open,turbulence;forced	For Ta,RH:Open,turbulence;forced

Table 6. Yazd configuration data for ENVI-met4 validation

Simulation parameters	Yazd	Ardabil
Simulation day	15.06.2015	23.06.2015
Simulation period	24h(21:00-21:00)	24h(21:00-21:00)
Spatial resolution	1m horizontally,2m vertically	1m horizontally,2m vertically
Initial Temperature	301.15	305.15
Wind speed	5m/s	1m/s
Wind direction (N=0,E=90)	135	0
Relative humidity(in 2m)	10.80%	8.5%
Indoor temperature	300K(27°C)	300K(27°C)
Initial Temperature Upper Layer (0-20 cm)	301.15	239
Initial Temperature Middle Layer (20-50 cm)	298.15	298.15
Initial Temperature Deep Layer (below 50 cm)	295.45	229.4
Relative Humidity Upper Layer (0-20 cm)	10.80%	8.5%
Relative Humidity Middle Layer (20-50 cm)	12%	10%
Relative Humidity Deep Layer (50 cm)	15%	13%
Adjustment factor for solar radiation	1	1
clouds	Default	Default
Turbulence model	Use default values	Use default values
LBC	For Ta,RH:Open,turbulence;forced	For Ta,RH:Open,turbulence;forced

For configuration file, four extra courtyard models have been modeled to reach the correct results in terms of the neighboring environment on the courtyard affects the output data, so accordingly the surrounding vegetation, pavement, and other real parameters are included in the simulation model. The measured and simulated Ta during the mentioned days in both cities are compared in Fig3 and 4.
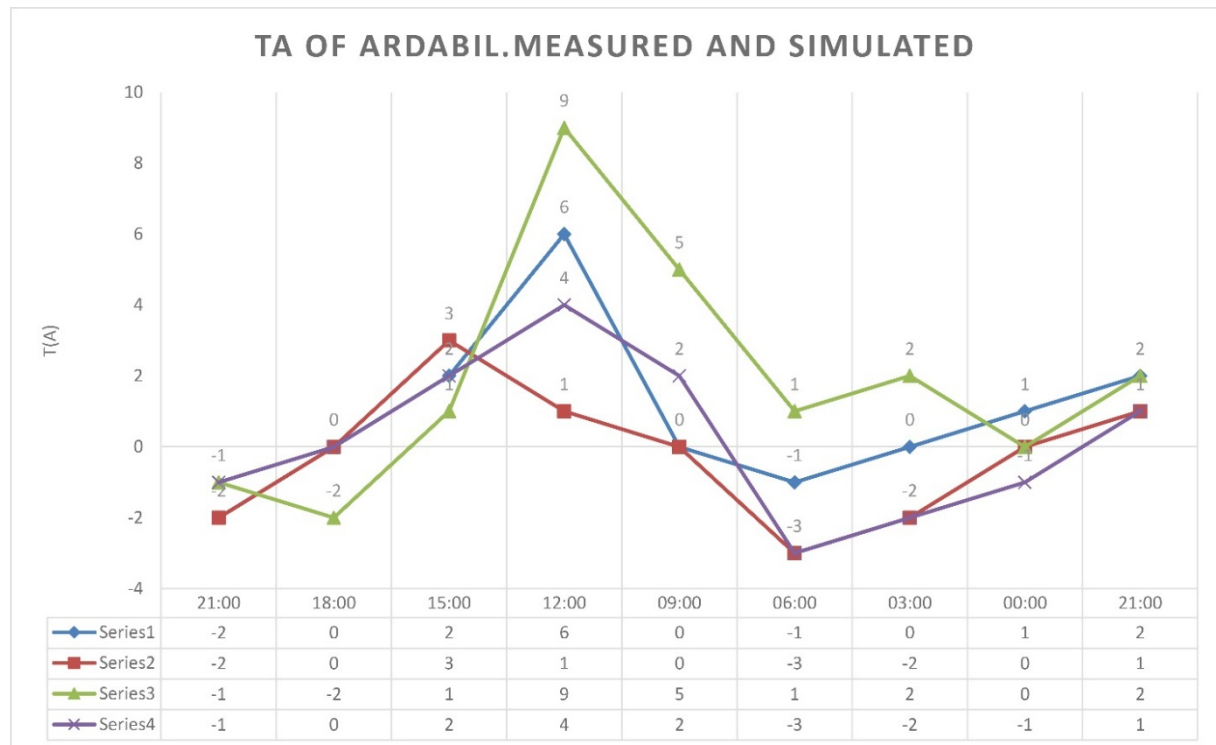
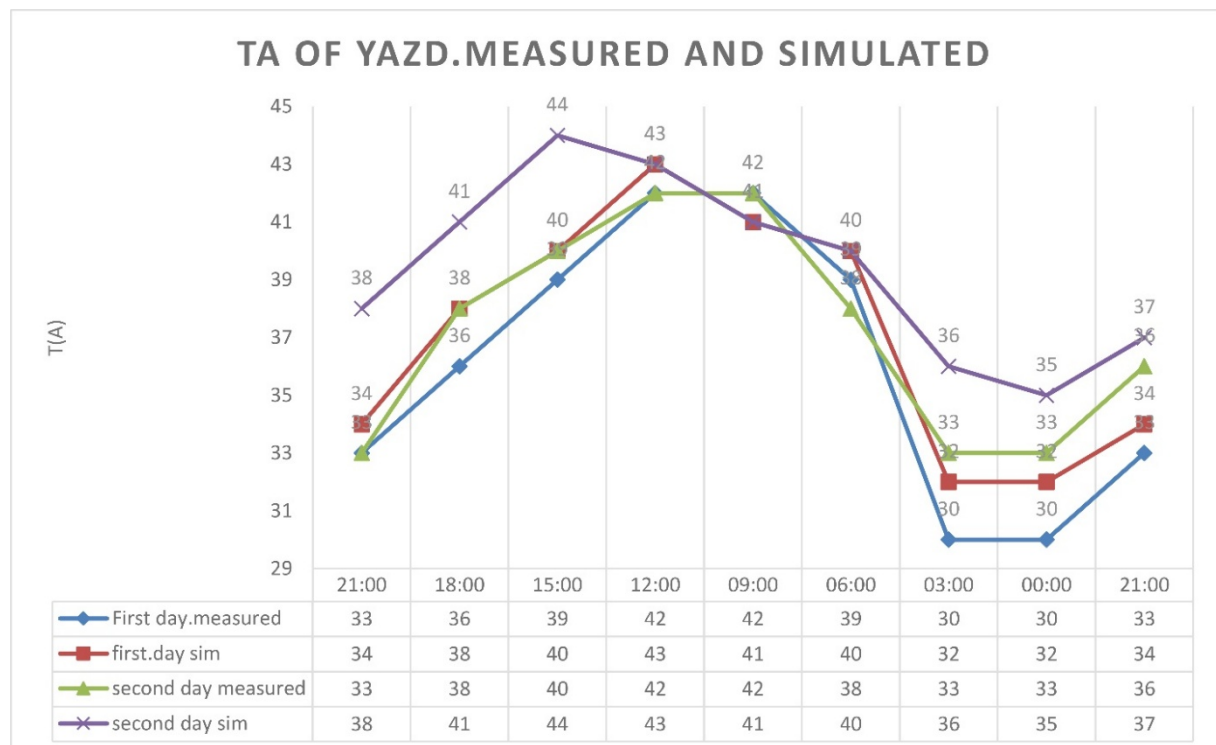Figure 3. Comparison of measured and simulated Ta in Ardabil

	21:00	18:00	15:00	12:00	09:00	06:00	03:00	00:00	21:00
Series1	-2	0	2	6	0	-1	0	1	2
Series2	-2	0	3	1	0	-3	-2	0	1
Series3	-1	-2	1	9	5	1	2	0	2
Series4	-1	0	2	4	2	-3	-2	-1	1

Figure 4. Comparison of measured and simulated Ta in Yazd

	21:00	18:00	15:00	12:00	09:00	06:00	03:00	00:00	21:00
First day.measured	33	36	39	42	42	39	30	30	33
first.day sim	34	38	40	43	41	40	32	32	34
second day measured	33	38	40	42	42	38	33	33	36
second day sim	38	41	44	43	41	40	36	35	37

Comparisons of the air temperature in both cities show that correlation of measured and simulated Ta in the first day in Ardabil is 82 % (R=0.82), and also R-value for the second day is 0.88. Therefore, on average, the correlation factor is 0.71 which means that more than 88% of ENVI-met outputs are reliable in the cold climate of Ardabil. Correlation analyses of simulated and measured air temperature in Yazd represent the high correlation

between simulated and measured Ta. The first-day's R-value is 0.98, and for the second day, it is 0.87. Therefore, ENVI-met outputs are completely reliable in the hot, arid climate of Yazd. The difference in the observed and simulated data could be the fact that ENVI-met does not include levels of cloudiness in its input parameters.

4.2 Physical Features of Traditional Courtyards of Ardabil & Yazd

4.2.1 Ardabil Traditional Courtyards

In this section, traditional courtyards of Ardabil were selected to be assessed in terms of physical features:

(i) The ratio of the courtyard area to total area of the house

(ii) The ratio of the water area to total area of the courtyard

(iii) The ratio of the vegetation area to total area of the courtyard

For this study, 8 traditional courtyards were selected to be investigated:

(i) Khadem house.

(ii) Sadeghi house.

(iii) Vakil Al-Roaya house

(iv) Reza Zadeh house.

(v) Ershadi House.

(vi) Ebrahimi House.

(vii) ManafZadeh House

(viii) Khalil Zadeh house.

Table 7. Physical features of Ardabil courtyard

Vegetation area/ courtyard	Water area/courtyard area	Total area/courtyard area	House name
0.5	0.04	0.51	Khadem house
0.36	0.03	0.48	Sadeghi house
0.00	0.00	0.22	Vakil Al-roaya house
0.43	0.02	0.51	Reza Zadeh house
0.00	0.00	0.22	Ershadi House
0.18	0.05	0.36	Ebrahimi House
0.37	.03	0.60	ManafZadeh House
0.09	0.02	0.46	.Khalil Zadeh house

4.2.2 Yazd Traditional Courtyards

In the second step, these 8 Yazd traditional courtyards were also selected to be assessed for the mentioned features:

(i) MehrabanGoodarz house

(ii) Lariha house

(iii) Gerami house

(iv) Golshan-e-Yazd house

(v) Kolahdoozha house

(vi) Arabha house

(vii) Mortaz house

(viii) Rasoulian house

The mentioned features were described in Table 8:

Table 8. Physical features of Ardabil courtyard

Vegetation area/ courtyard	Water area/courtyard area	Total area/courtyard area	House name
0.08	0.04	0.16	MehrabanGoodarz house
0.19	0.12	0.21	Lariha house
0.23	0.15	0.24	Gerami house
0.15	0.21	0.22	Golshan-e-Yazd house
0.20	0.15	0.26	Kolahdoozha house
0.10	0.10	0.25	Arabha house
0.25	0.14	0.38	Mortaz house
0.10	0.17	0.30	Rasoulian house

4.2.3 Comparison

In a comparison of the data derived from the previous tables, it can be concluded that in Yazd's hot-arid climate, due to a long and hotter summer, more water ponds were used. This is in contrast with the rough, cold climate of Ardabil where only a small area of water covers the courtyard. In terms of vegetation, a smaller area of courtyards in Yazd is covered by trees to reach optimum natural ventilation. In Ardabil's cold climate, this percentage is more than Yazd. About total area of the courtyard in these two contrasting climates, the averages of the courtyard is about 42% of the total plan and 0.26% of the total plan consider as a courtyard. In table 9, a comparison of these mentioned features is portrayed:

Table 9. Comparison of the physical features of both climate

Vegetation area/ courtyard	Water area/courtyard area	Total area/courtyard area	city
0.23	0.03	0.42	Ardabil
0.18	0.14	0.26	Yazd

4.3 Results of Simulations

The study scrutinized different courtyard configurations. The sample building and its courtyard dimension were chosen by the average of the real traditional courtyard houses of Ardabil and Yazd. The 360m^2 (60*60 m) 2-story building (8 meters of height) and the other parameters of the courtyard (dimension, water amount, and the vegetation) were selected based on the minimum and maximum of the real courtyard houses of the Ardabil and Yazd.

4.3.1 Effect of the Courtyard Area

As a first step, it is crucial to determine the courtyard area percentage based on local climate. So, in this regard, 10, 20, 40 and 60 percent of the block was considered as a courtyard and simulated for both climates.

The impact of the different areas towards influencing the microclimate features such as relative humidity, wind velocity, Tmrt, and the ambient temperature were measured recording the different factors on the values assumed by previous parameters in the center of the courtyard spaces.

4.3.1.1 Ardabil Courtyard Area

A comparison of the courtyards in terms of the area shows that the average air temperature in all four conditions is stable, and is about -11. The differences between the highest and the lowest one is 0.4 °C (10%= -11.475, 20= -11.656, 40%= -11.856 and 60%= -11.906). However in terms of Tmrt, there is a different condition. The difference between the highest and the lowest is 11.73°C. The hourly frequency of Tmrt is described in Fig 5. Based on this Fig, (in all conditions) at the beginning of the morning (7.00-8:00 am) Tmrts are in the equal range. This is also true for the end of day (16.00-18:00 pm), but in the next hours, Tmrt of 60% area grows more quickly than the others, which means that the average air temperature of the Tmrt for 60% is higher than the

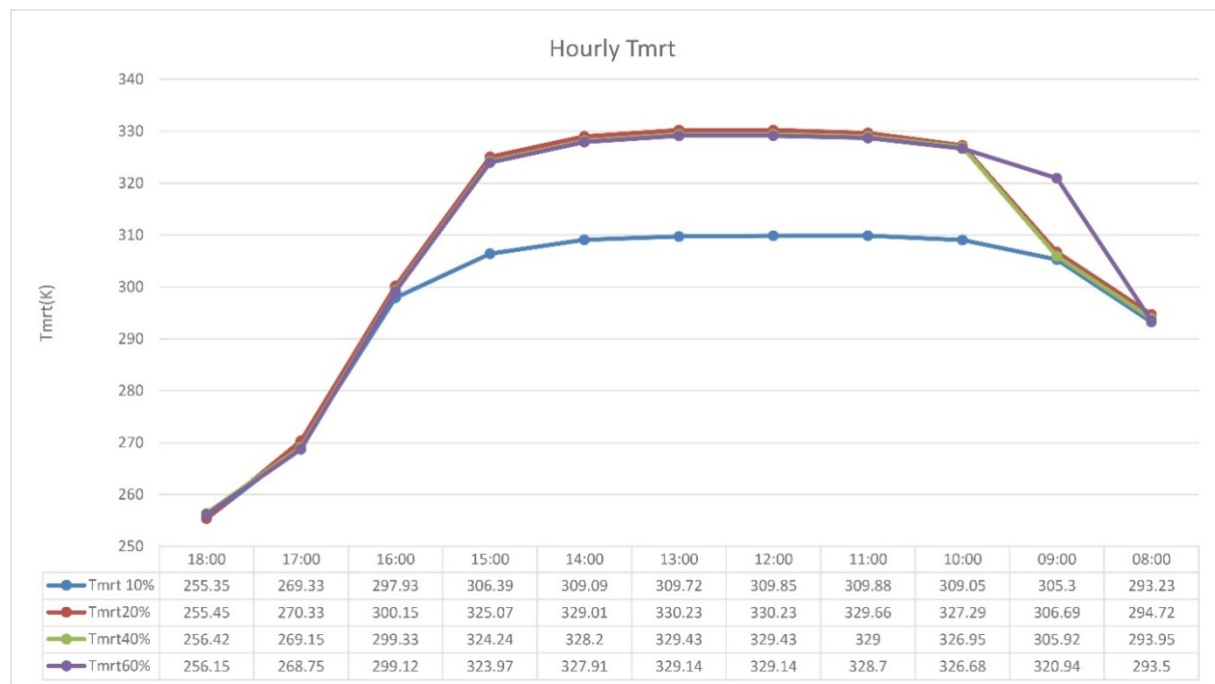others (10%=24.58°C, 20%35.84°C, 40%=35.22°C, 60%=36.31°C).

	18:00	17:00	16:00	15:00	14:00	13:00	12:00	11:00	10:00	09:00	08:00
Tmrt 10%	255.35	269.33	297.93	306.39	309.09	309.72	309.85	309.88	309.05	305.3	293.23
Tmrt20%	255.45	270.33	300.15	325.07	329.01	330.23	330.23	329.66	327.29	306.69	294.72
Tmrt40%	256.42	269.15	299.33	324.24	328.2	329.43	329.43	329	326.95	305.92	293.95
Tmrt60%	256.15	268.75	299.12	323.97	327.91	329.14	329.14	328.7	326.68	320.94	293.5

Figure 5.Hourly frequency of Tmrt of Ardabil

Wind velocity is another important parameter of outdoor thermal comfort and was also investigated in these courtyards. There were not any significant differences between the conditions in terms of average wind speed. On average, there is a 0.251 m/s difference between the highest and the lowest velocity (10%=3.958m/s, 20%=3.881, 40%=3.763 and 60%=3.701m/s).

The average figures for the PET values in these courtyards demonstrates 3-degree differences (10%=-13.1°C, 20%=-11.6, 40%=-10.9, 60%=-10.6) between all conditions. The 60% courtyard has a better condition, and because of its open sky condition, the 60% courtyard reaches longer direct and diffuse radiation and by this means R-value (correlation) between PET value and Tmrt, SW.dir, SW.diff are 0.915, 0.9, and 0.8715.

Hourly frequency of PET is described in Fig6. In FIG7, Leonardo visualization describes the Tmrt and wind speed conditions in a different configuration.
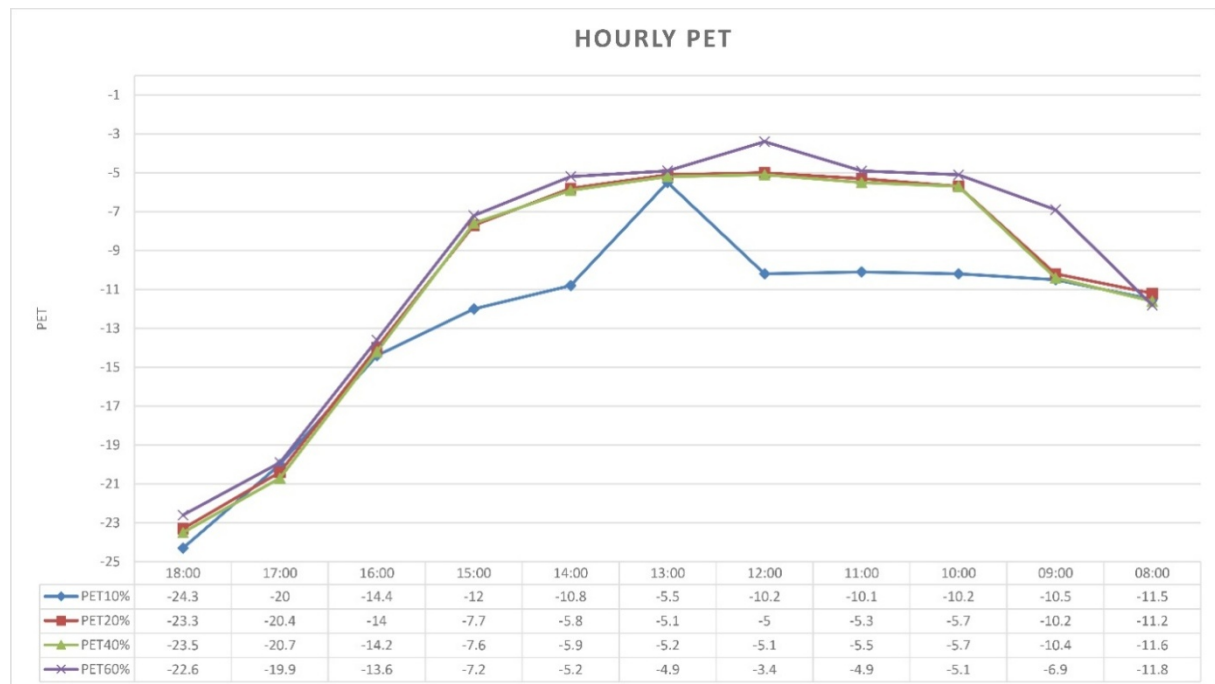
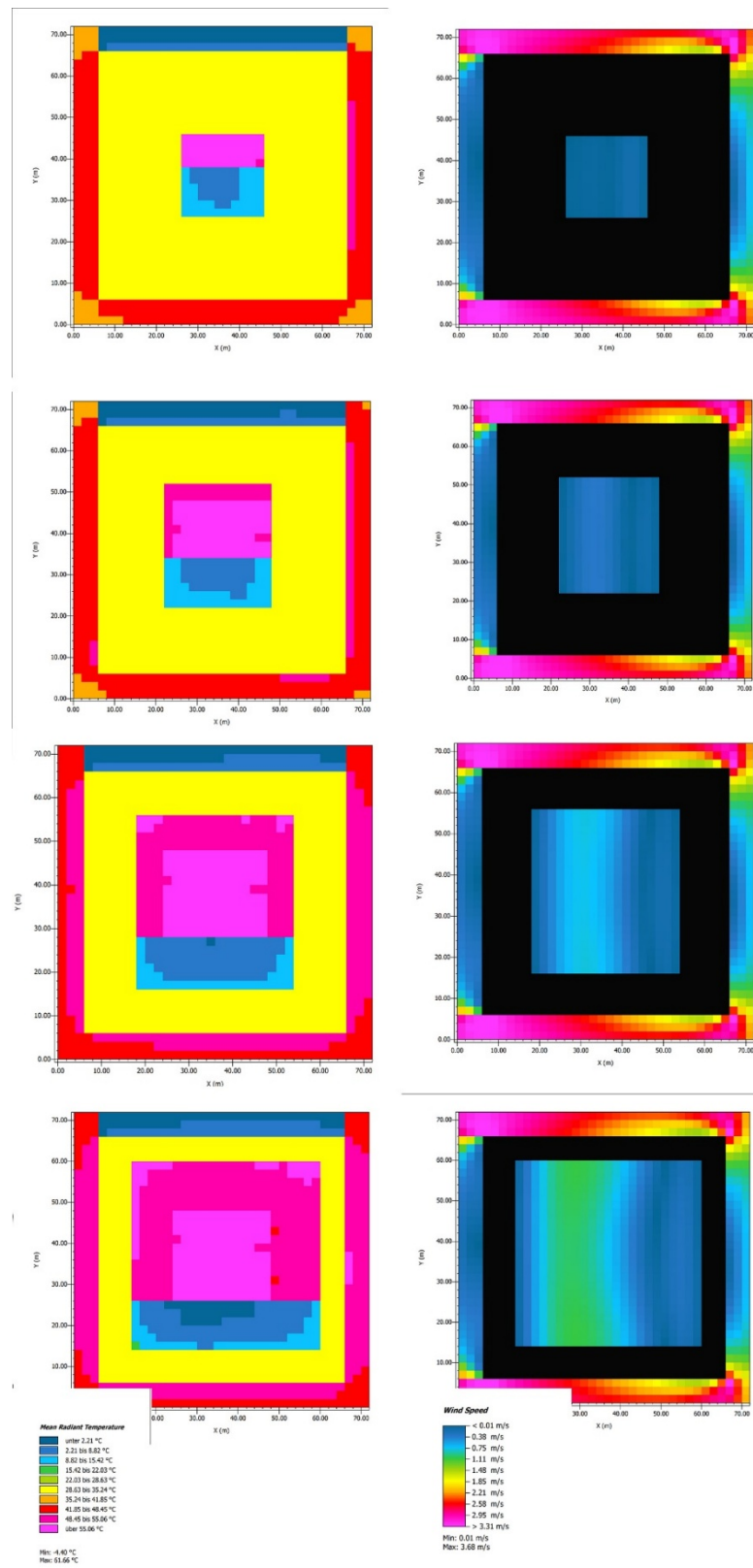Figure 6. Hourly frequency of PET based on area. Ardabil

Figure 7. Tmrt and Wind speed condition of Ardabil courtyard (Leonardo)

4.3.1.2 Yazd Courtyard Is

The courtyards were compared with their related Ta and the results show that there are not that many differences between the courtyards (10% = 24.89°C, 20% = 24.92, 40% = 24.94, 60% = 25°C). However, the different sky exposure means that the Tmrt values are different, and by this means there are 3.17°C differences between the maximum and the minimum Tmrt. The hourly frequency of Tmrt is described in Fig 8. Based on this Fig, in all conditions, at the beginning (7.00-8:00 am) of the morning, the mean radiant temperature values are in the equal range but as the sun rises the radiation amount increase too.
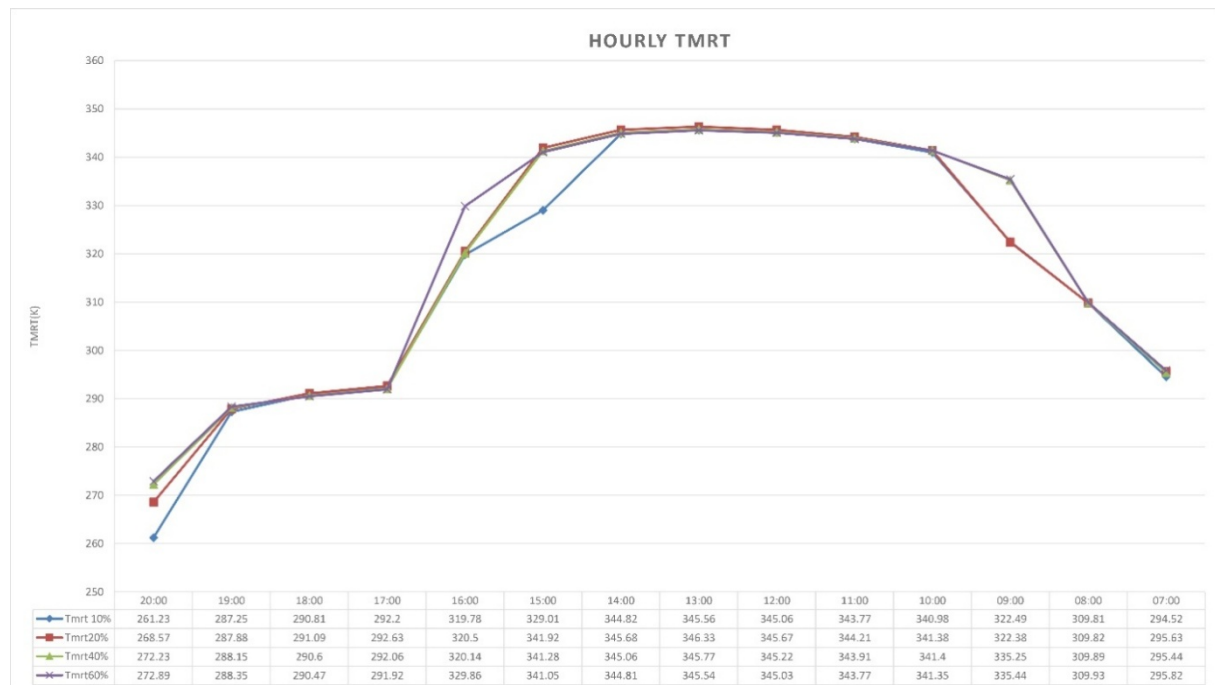

HOURLY TMRT

	20:00	19:00	18:00	17:00	16:00	15:00	14:00	13:00	12:00	11:00	10:00	09:00	08:00	07:00
Tmrt 10%	261.23	287.25	290.81	292.2	319.78	329.01	344.82	345.56	345.06	343.77	340.98	322.49	309.81	294.52
Tmrt20%	268.57	287.88	291.09	292.63	320.5	341.92	345.68	346.33	345.67	344.21	341.38	322.38	309.82	295.63
Tmrt40%	272.23	288.15	290.6	292.06	320.14	341.28	345.06	345.77	345.22	343.91	341.4	335.25	309.89	295.44
Tmrt60%	272.89	288.35	290.47	291.92	329.86	341.05	344.81	345.54	345.03	343.77	341.35	335.44	309.93	295.82

Figure 8. Hourly frequency of Tmrt of Yazd

In the next few hours, the 60% courtyards' Tmrt grows, quicker than the other courtyards'. Based on the graph, the thermal behavior of all conditions between 10:00-14:00 are equal, but the 10% courtyard loses its Tmrt faster than the others and at the end of the day (20:00) it reaches the lowest Tmrt among the courtyards. Therefore, on average, the 10% courtyard has the lowest Tmrt (10% = 52.69°C, 20% = 54.26, 40% = 55.08, 60% = 55.86°C).

The average PET value in each courtyard represents a 1.8°C difference (10% = 31.4°C, 20% = 32.2, 40% = 32.6. 60% = 33.2) between all conditions. The 10% courtyard has a better condition, and because of the closer sky condition of the 60% courtyard, it reaches less long direct and diffuse radiation. This means the R values (correlation) between PET value and Tmrt, SW.dir, and SW.diff are 0.95, 0.94, and 0.96. The hourly frequency of related PET is described by Fig9. In FIG 10, Leonardo visualization describes the Tmrt and wind speed conditions in a different configuration.
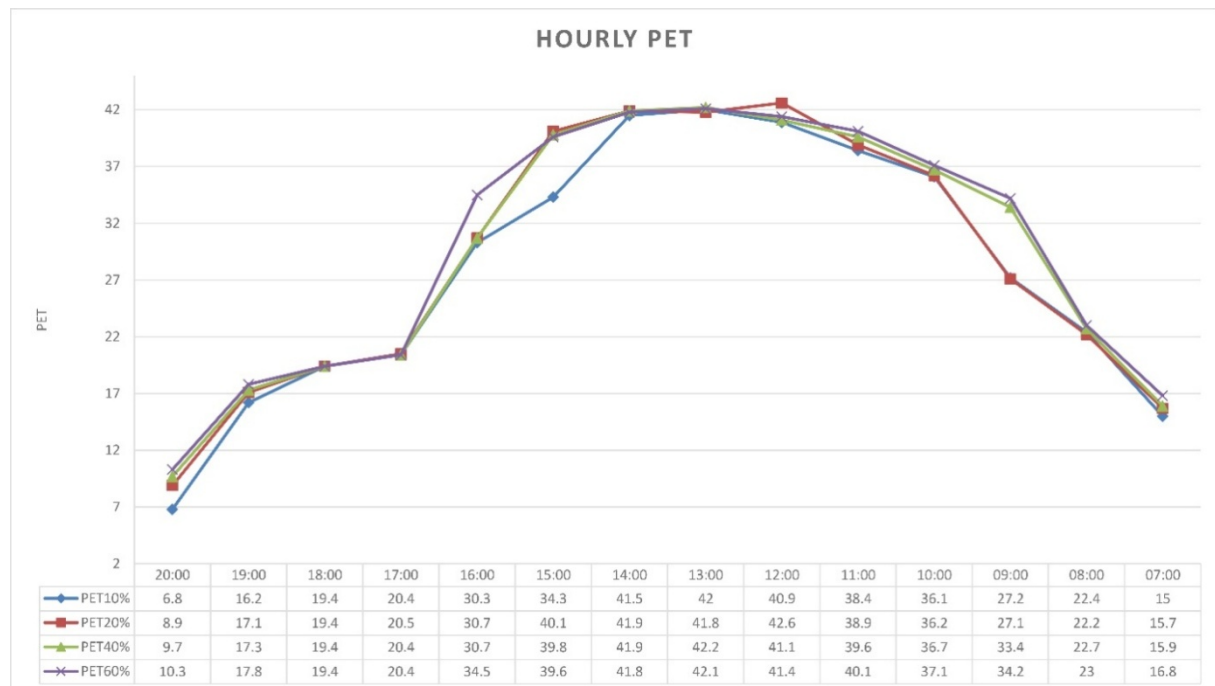
Figure 9. Hourly frequency of PET based on area.Yazd

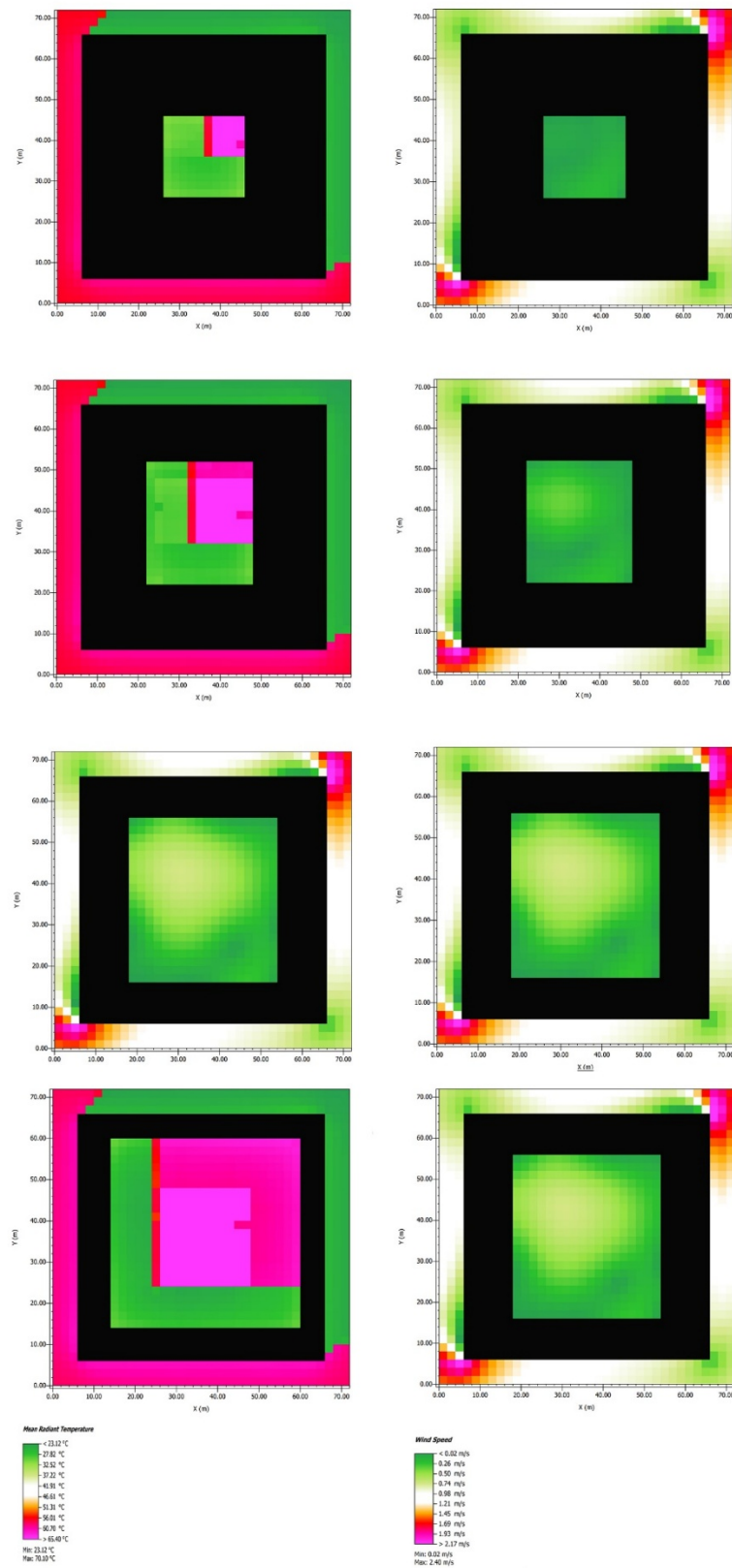Figure 10. Tmrt and Wind speed condition of Yazd courtyard(Leonardo)

4.3.2 Effect of Courtyard Water Level

The presence of water in Iranian traditional courtyards is a common principle, and water is also the main component of contemporary courtyards. This means that 0, 10, 15, and 20 are the typical percentages of water in traditional courtyard areas in both climates. In this regard, these percentages have been considered as a courtyard and simulated for both climates.

The impact that different water amounts have upon microclimate features such as relative humidity and Tmrt was considered when recording the different factors for the values assumed by previous parameters in the center of the courtyard spaces.

4.3.2.1 Ardabil Water Amount Analyze

A comparison of the water level in the 60% area highlights the fact that air temperatures are in a roughly equal range (0% = -12.26°C, 10% = -12.33, 15% = -12.36, 20% = -11.62). It also demonstrates that owing to the cold air temperature, the relative humidity of these conditions is 100%, and, accordingly, the wind speed parameter is equal to all conditions. Radiant temperatures differ notably with different water amounts. The courtyard contains 0% water featured 10°C higher on the Tmrt scale (0% = 36.49°C, 10% = 26.24, 15% = 26.26, 20% = 26.56), and the hourly frequency of the Tmrt is described in Fig11.

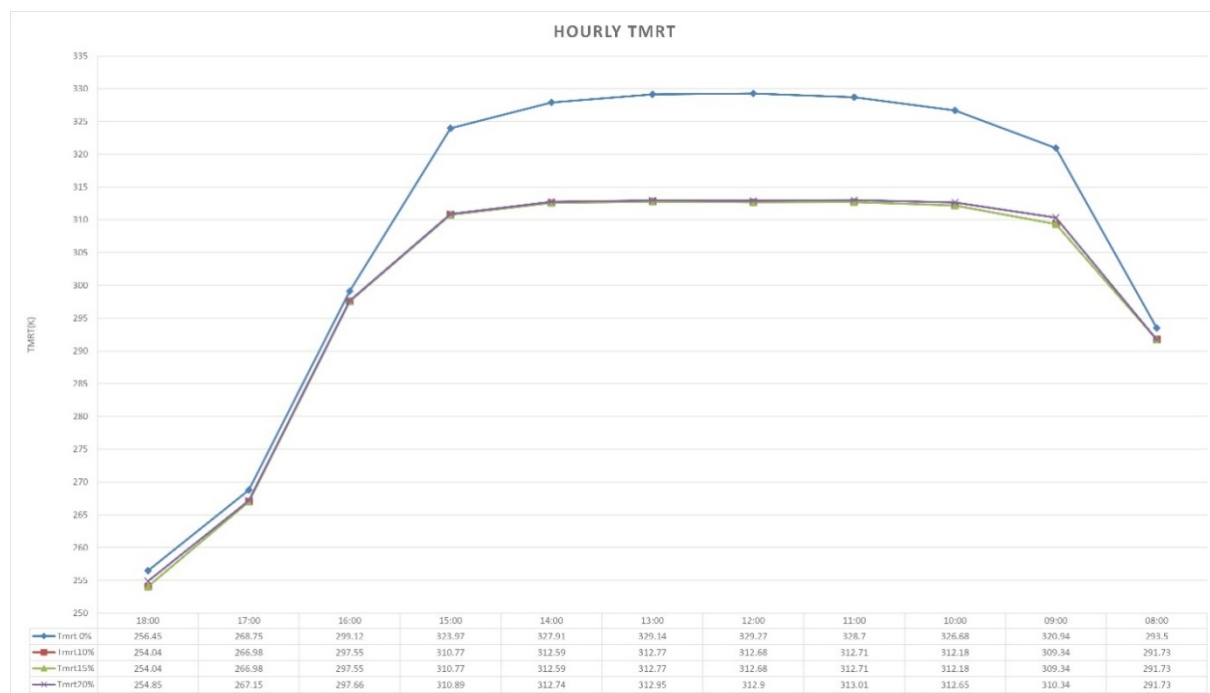|	18:00	17:00	16:00	15:00	14:00	13:00	12:00	11:00	10:00	09:00	08:00
Tmrt 0%	256.45	268.75	299.12	323.97	327.91	329.14	329.27	328.7	326.68	320.94	293.5
Tmrt10%	254.04	266.98	297.55	310.77	312.59	312.77	312.68	312.71	312.18	309.34	291.73
Tmrt15%	254.04	266.98	297.55	310.77	312.59	312.77	312.68	312.71	312.18	309.34	291.73
Tmrt70%	254.85	267.15	297.66	310.89	312.74	312.95	312.9	313.01	312.65	310.34	291.73

Figure 11. Hourly frequency of Tmrt(water amount)

According to the seven, all other conditions except the 0% have a colder Tmrt. At the beginning of the referenced day (7.00-8:00 am), all conditions have equal Tmrt but by sunrise, the thermal behavior of the courtyards changes - the courtyard containing no water reaches the highest Tmrt. Then, from 9:00 to 16:00, it maintains the highest Tmrt. At the end of the day, the thermal behavior of the courtyards is similar to each other. The main atmospheric parameters of these courtyards are approximately equal, but Rlw warming has a different value for each courtyard. These values represent the air temperature change due to longwave flux divergence. This value shows higher changes compared to the others (0% = 0.65 K/h, 10% = 0.43, 15% = 0.41, 20% = 0.44 K/h), and higher air temperature variations based on long wave flux divergence will definitely cause higher Tmrt.

The results discussed in this section are represented by PET thermal index. On average, the courtyard containing 0% water in the cold climate of Ardabil has a better thermal condition than the other conditions (0% = -10.8, 10% = -13.1, 15% = -13.1, 20% = -12.4°C). The hourly frequency of PET is described in Fig 12.
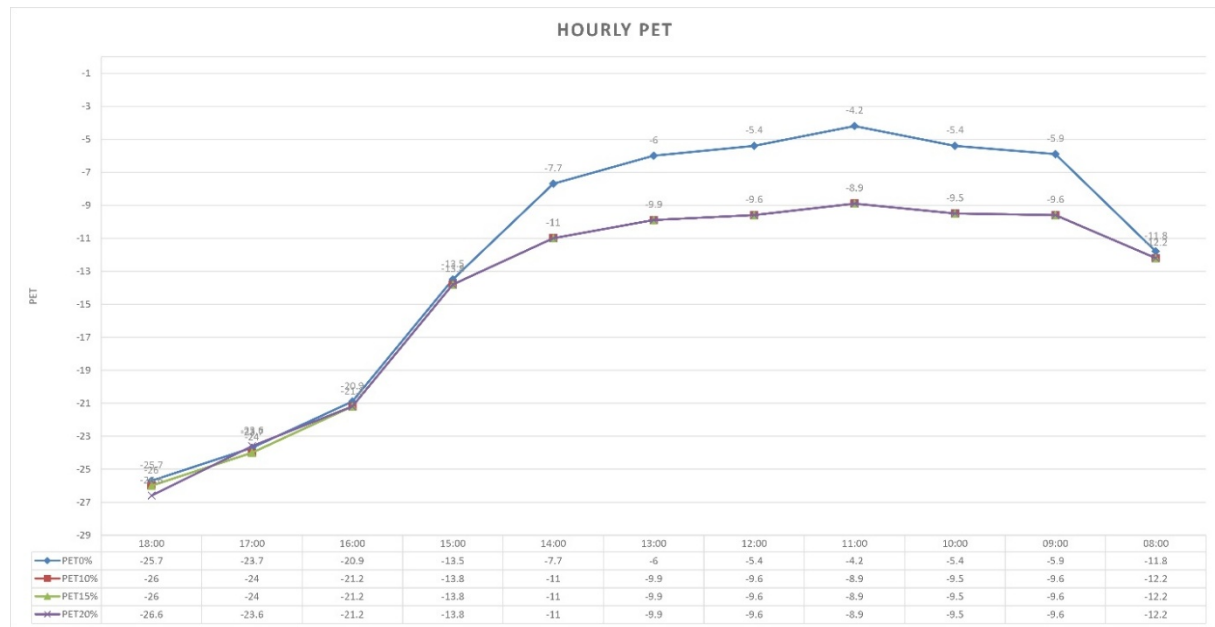
Figure 12. Hourly frequency of PET based on water.Ardabil

4.3.2.2 Yazd Water Amount Analyze

A comparison of the results of the water levels in the 10% area (as a better condition of courtyards) shows that air temperatures are different with different amounts of water (0 & 10 % = 24.36°C and 15 & 20% = 27.5). It also shows that the relative humidity is changed by Ta changing and water percentage. There is a 3.41% difference between the highest and lowest relative humidity of the courtyards (0 & 10% = 56.05%, 15 & 20% = 52.65%). Accordingly, there are different Tmrt in these courtyards based on different levels of water percentage. On average, the courtyard that is covered 10% by water has the better thermal condition and it is 9.05°C cooler than the hottest courtyard (0% = 44.25°C, 10% = 38.58°C, 15&20% = 47.53°C). The hourly frequency of the mean radiant temperatures of courtyards is described in Fig13.
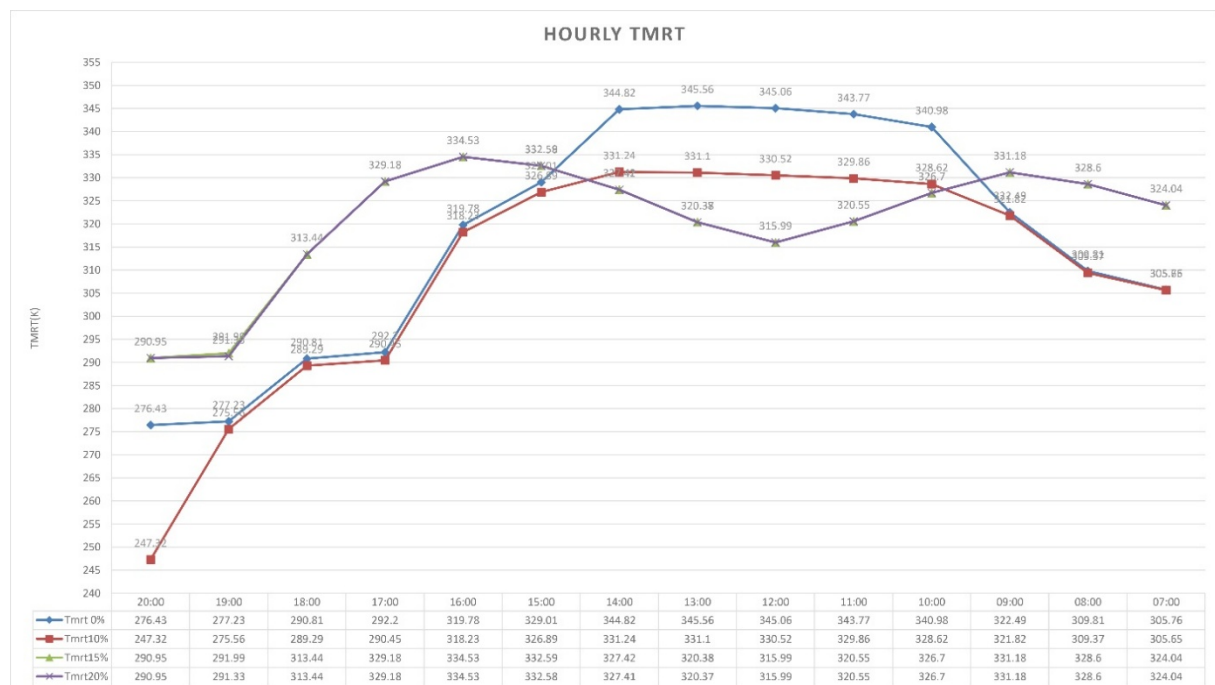

Figure 13. Hourly frequency of Tmrt of Yazd(water amount)

Based on Fig13, with the exception of the 20% courtyard, the courtyards have equal Tmrt at the beginning of the morning. By sunrise, the thermal behavior of the courtyards is different. At 12:00, the 0% courtyard has the highest and the 15% and 20% have the lowest Tmrt. The 10% is in the middle. In the afternoon, the 20% is still in the highest condition, but the 10% reaches the lowest Tmrt and - according to what has been discussed before - on average. The 10% courtyard has a 10°C cooler environment in terms of Tmrt. The PET values of these conditions have been calculated and the results demonstrate that, on average, the 10% courtyard has a more comfort condition (0% = 27.6°C, 10% = 25.4°C, 15 & 20% = 31.9°C). The hourly frequency is described in Fig14.
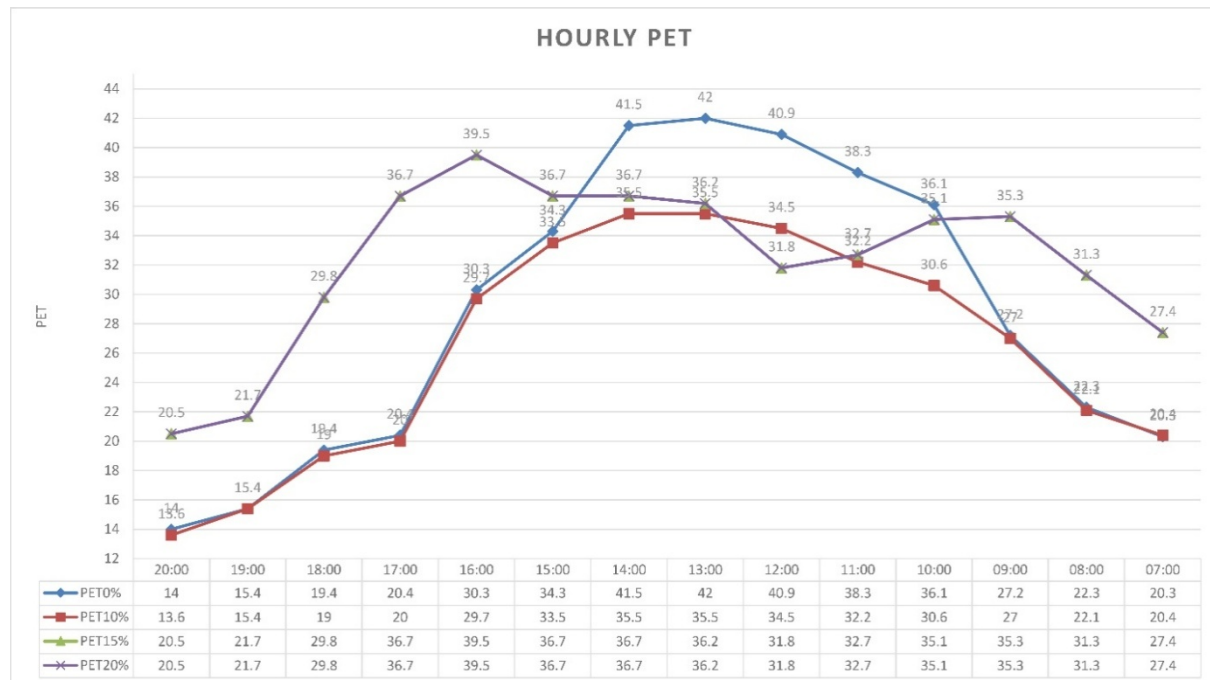
HOURLY PET

	20:00	19:00	18:00	17:00	16:00	15:00	14:00	13:00	12:00	11:00	10:00	09:00	08:00	07:00
PET0%	14	15.4	19.4	20.4	30.3	34.3	41.5	42	40.9	38.3	36.1	27.2	22.3	20.3
PET10%	13.6	15.4	19	20	29.7	33.5	35.5	35.5	34.5	32.2	30.6	27	22.1	20.4
PET15%	20.5	21.7	29.8	36.7	39.5	36.7	36.7	36.2	31.8	32.7	35.1	35.3	31.3	27.4
PET20%	20.5	21.7	29.8	36.7	39.5	36.7	36.7	36.2	31.8	32.7	35.1	35.3	31.3	27.4

Figure 14. Hourly frequency of PET based on water amount.Yazd

4.3.3 Effect of Vegetation

Green spaces and utilization of vegetation in the courtyard will modify the different environmental parameters in open spaces and also in courtyards. Based on the traditional courtyards in both climates, four levels of greening were examined and stimulated with 0%, 20%, 40% and 60% of the courtyard being covered by vegetation. The use of different vegetation will affect the climatic features such as Ta, Tmrt, wind speed and humidity. These results were recorded using the values assumed by previous parameters in the center of the courtyard spaces.

4.3.3.1 Microclimatic Effect of Vegetation in the Courtyard of Ardabil

In this section, as a final step, the different levels of greening were simulated in the best area percentage of the courtyard in the very cold climate of Ardabil. A comparison of the data shows that the air temperature of different greening conditions varies by 1.6°C (0% = -11.475°C, 20% = -12.38°C, 40% = -12.87°C, 60% = -13.1°C). As was the case because of frozen degrees, the relative humidities of all conditions are 100%, besides the Ta, wind velocities and mean radiant temperatures are changing correspondingly by vegetation changes. On average, the wind speed of the courtyards are decreasing with the vegetation percentage (0% = 3.96, 20% = 3.23, 40% = 2.99, 60% = 2.9°C), and there is 1.06 m/s of difference between the 60% tree-covered spaces and non-covered one.

The next step is to calculate the PET thermal index. The mean radiant temperatures were used to analyze the effect of vegetation on outdoor thermal comfort. Therefore, on average the 20% covered courtyard has the highest Tmrt on the coldest day of winter (0% = 24.58, 20% = 31.49, 40% = 26.05, 60% = 24.49°C).The hourly frequency of Tmrt is described in Fig15.

	18:00	17:00	16:00	15:00	14:00	13:00	12:00	11:00	10:00	09:00	08:00
Tmrt 0%	255.35	269.33	297.93	306.39	309.09	309.72	309.85	309.88	309.05	305.3	293.23
Tmrt20%	266.85	288.21	302.23	311.3	313.87	315.46	315.78	315.21	313.93	314.6	293.66
Tmrt40%	255.85	270.25	298.23	307.37	310.49	311.35	311.61	311.39	310.43	310.73	293.59
Tmrt60%	256.31	270.85	298.06	306.6	309.21	309.85	310.03	310.09	309.36	310.1	283.62

Figure 15. Hourly frequency of Tmrt based on vegetation percentage

According to the calculation formula of the Tmrt in ENVI-met model in its initial stage, (Thorsson et al., 2007):

$$Tmrt = \left[(GT + 273.14^4 + \frac{1.1 * 10^8 Va^{0.6}}{\delta * D^{0.4}} * (Tg - Ta) \right].^{1/4} 273.15$$

Where

Tmrt is the mean radiant temperature (K),

GT is the globe temperature (K),

Va is the air velocity near the globe (m/s),

δ is the emissivity of the globe which normally is assumed 0.95,

D is the diameter of the globe (m) which typically is 0.15 m, and

Ta is the air temperature (K).

Accordingly, Tmrt is the total amount of direct and diffuse radiation on a specific point. Wind speed has an inverted effect on the Tmrt by $10^8 * 0.6$ near to Globe. This means that an increase in wind velocity results in a decrease in radiant temperature, so Tmrt is affected by SWdir, SWdiff and also wind speed. In the 20% covered courtyard, the sum of wind speed and the radiation amount create suitable for a combination of these two. So the PET average values (0% = -12.68, 20% = -10.60, 40% = -12.06, 60% = -12.61°C) show that the 20% courtyard is 2°C warmer on the PET scale. The hourly frequency of PET is described in Fig 16:
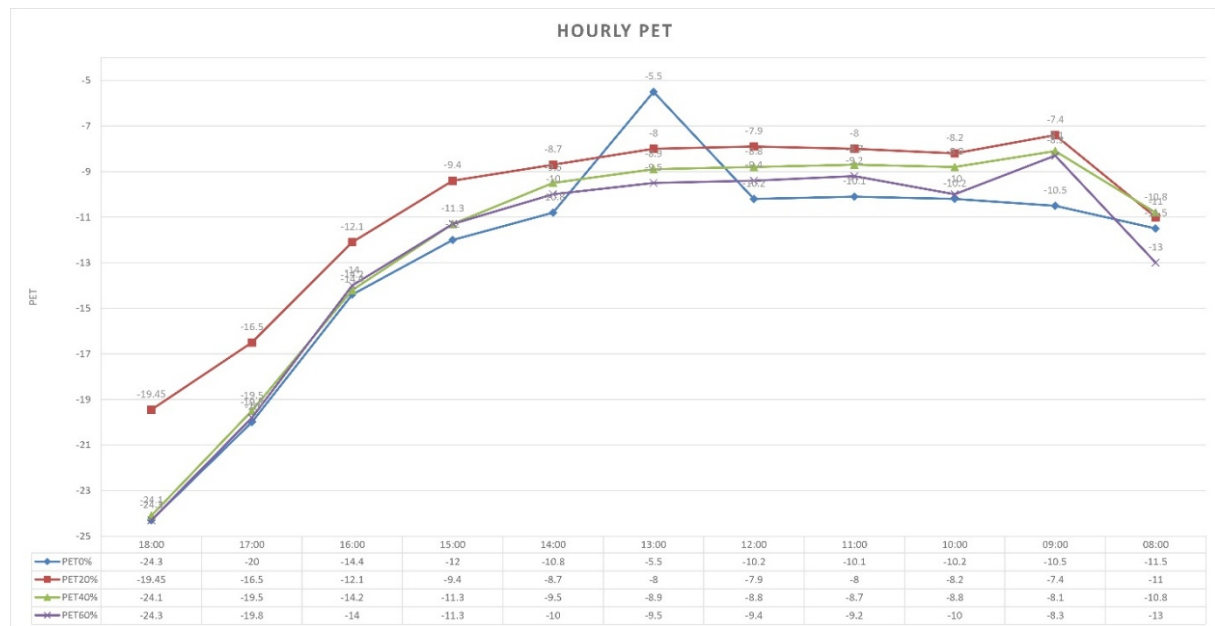
Figure 16. Hourly frequency of PET based on vegetation in Ardabil

According to Fig 16, the 20% covered courtyard achieves the highest PET value.

4.3.3.2 Microclimatic Effect of Vegetation in the Courtyard of Yazd

Based on the methods used in Ardabil courtyards, the effects of vegetation were investigated by simulation. In comparison of Ta, the results shows that there is less than 0.25°C between the maximum and minimum (0% = 24.51, 20% = 27.31, 40% = 27.27, 60% = 27.24°C). In contrast to the conditions in Ardabil, there is different relative humidity due to the different Ta and vapor content of the air. On average, there is 1.28% difference between the highest and lowest relative humidity in these simulations (0% = 52.64, 20% = 53.33, 40% = 53.67, 60% = 53.92°C). Wind velocities are changing in line with alterations to vegetation levels, and by increasing the vegetation percentage in these courtyards wind speeds are decreased (0% = 2.35, 20% = 1.92, 40% = 1.60, 60% = 1.43°C). On average, the 20% courtyard has the lowest Tmrt (0% = 59.32, 20% = 54.65, 40% = 56.45, 60% = 56.32°C) . Hourly frequency of Tmrt is described in Fig17.
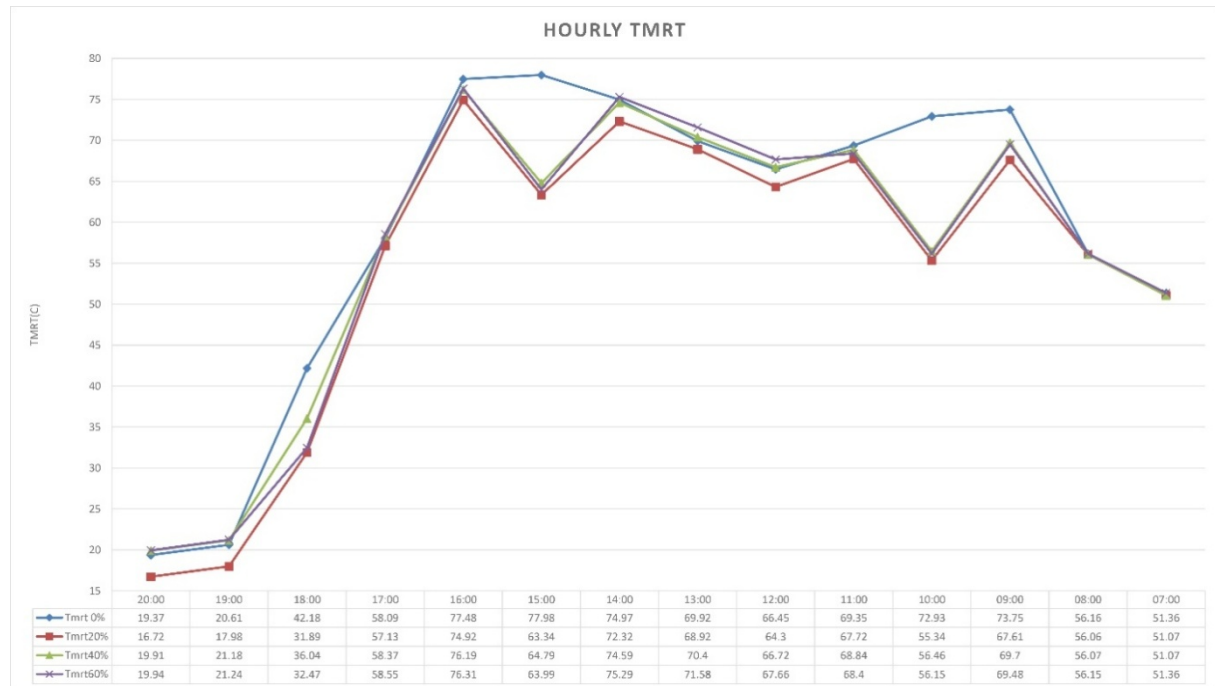
	20:00	19:00	18:00	17:00	16:00	15:00	14:00	13:00	12:00	11:00	10:00	09:00	08:00	07:00
Tmrt 0%	19.37	20.61	42.18	58.09	77.48	77.98	74.97	69.92	66.45	69.35	72.93	73.75	56.16	51.36
Tmrt20%	16.72	17.98	31.89	57.13	74.92	63.34	72.32	68.92	64.3	67.72	55.34	67.61	56.06	51.07
Tmrt40%	19.91	21.18	36.04	58.37	76.19	64.79	74.59	70.4	66.72	68.84	56.46	69.7	56.07	51.07
Tmrt60%	19.94	21.24	32.47	58.55	76.31	63.99	75.29	71.58	67.66	68.4	56.15	69.48	56.15	51.36

Figure 17. Hourly frequency of Tmrt based vegetation in Yazd

The Tmrt were derived and compared in order to determine the coolest courtyards in terms of vegetation different percentages. The results show the 20% covered has the lowest Tmrt among all conditions. According to what has been discussed in the previous section, and based on a formula to have a lower Tmrt, the courtyard needs less direct and diffuse radiation and also high wind speed. The optimum combination of vegetation and wind speed occurs in a 20% courtyard.

The final step is to calculate the PET thermal index by Rayman 1.2, to find each average (0% = 37.3, 20% = 35.37, 40% = 37.21, 60% = 37.7°C).

In order to assess the comfort condition, the hourly frequency of PET value described in FIG18.

Figure 18. Hourly frequency of pet based on vegetation in Yazd

As shown in Fig12, the 20% tree-covered courtyard has a significantly cooler PET value based on what has previously been explained. This courtyard has the best combination of wind speed and tree coverage.

5. Conclusion

Open spaces and their quality roughly depend on their thermal condition. Better thermal comfort condition of courtyards was proved in many types of research, and it is a common strategy in traditional architecture to modify the climatic conditions. Courtyards were mostly investigated in hot-arid and humid conditions. Uniform use of the courtyards in a different climate is a contemporary architecture issue. Therefore, a study of the physical features of traditional courtyards in a different climate in Iran could be undertaken. The results could then be compared to those found in Iranian conditions, and contextual guidelines for courtyards in fewer arid conditions could be drawn up.

Accordingly, the thermal comfort achieved during the critical day of each climate (rough clod of Ardabil, hot-arid of Yazd) was selected to assess the thermal comfort condition in low contrast courtyards. Results presented new practical guidelines as to how to best adapt the contemporarily-built environment with the climate based on traditional factors to reach sustainable contextual courtyards. Reliable simulation methods present optimum solutions to create thermally comfortable courtyards in the real world. As a first step, physical features of 16 traditional courtyards of both climates were analyzed. Three main features of the courtyard were considered in analyzing:

    (i)   The ratio of the courtyard area to the total area of the house

    (ii) The ratio of the water area to the total area of the courtyard

    (iii) The ratio of the vegetation area to the total area of the courtyard

Based on the results of this section, the range of the simulation parameters was determined.

1) Initially, in order to have optimum solar radiation in both direct and diffuse conditions, the area of the courtyard was simulated. The simulation showed that the optimum courtyard size for the hot and arid climate of Yazd was 10% of the total area of the house. In contrast, to have more radiation in the rough winters of Ardabil, the optimum courtyard size is 60% of the total area of the house. Based on the PET results, there are 6.8°C differences between the 10% and 60% courtyards area in Ardabil, and by increasing the sky exposure condition the60% courtyard reaches the more SW.dir and SW.diff. Therefore, high Tmrt causes high PET values. In contrast, the area percentage of the courtyards of Yazd, due to having less solar radiation in hot summer day 10% percent courtyard area were recommended with ENVI-met4 results. By this means in average the 10% courtyard

area reaches less solar radiation and it has more shaded surfaces on a hot summer day of Yazd. Pet results demonstrate the cooler environment of Yazd accordingly at 15:00 there is a 9.8°C differences between the hottest and the coolest courtyard.

2) The second step was to analyze the effect of using water as the main component in a traditional courtyard. The ratio of the water area to the total area of courtyards was simulated, and the results show that every condition except the 0% (water) courtyards produced a cooler environment in very cold winter of Ardabil (as happens in traditional courtyards). There was a 16.59°C difference between the 0% courtyards and the others at 13:00. PET values demonstrate the warmer environment of a 0% courtyard in comparison with the others by 4.7°C of PET.

Water area simulation results for Yazd's hot climate demonstrate that 10% of the water area is the optimum option in the hot and arid climate of Yazd. However, at 12:00 the 20% water courtyard has the coolest environment. During the day it has a high Tmrt temperature, but the 10% water area courtyard has a low temperature rather than the other models in average condition (during the referenced day).

3) The final step in courtyard simulation. The courtyards were simulated in 4 conditions (0%, 20%, 40%, and 60% tree covered area). At the Tmrt calculation formula present, it is summed up the direct and diffuse radiation and it is affected by wind speed inversely. The optimum conditions in which to have higher Tmrt in the presence of vegetation is a 20% tree covered area. The PET values of the show that effectively the 20% courtyard has a warmer environment in the rough, cold winter day in Ardabil.

These conditions were simulated to the hot-arid climate of Yazd, and the results show that the optimum tree covering of 20% results in less radiation and enough wind speed in the Yazd hot-arid climate. The hourly frequency of the Tmrt shows that, on average, there are 4.65°C differences between the highest and lowest Tmrt and accordingly the results of PET values demonstrate that among the different tree coverage, the 20% tree covered courtyard has better conditions than the others and, on average, has a 2.33°C cooler environment than the hottest one.

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