THERMAL BEHAVIOR IN THE TRADITIONAL COURTYARD HOUSES OF YEMEN

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THERMAL BEHAVIOR IN THE TRADITIONAL COURTYARD HOUSES OF YEMEN

by

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Thesis submitted in fulfillment of the
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LIST OF ABBREVIATION

ΔT	Temperature difference
ΔS	Change in heat store
3D	Three Dimensions
A	Area (m^2)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	Computational Fluid Dynamic
CLEAR	Comfortable Low Energy ARchitecture
DCHn	Deep Courtyard House Number of case
g/kg	Grams of Moisture Per Kilogram of Dry Air
G.W/H	Gig Watt per Hour
H	Height
K	Thermal Conductivity (W/M°C)
K	Kelvin (unit of temperature)
Kg/m^3	Density (Unit energy flow rate through unit area)
Kj/K°c	Specific heat (Energy required by substance for unit temperature increase “per unit mass or unit volume”)
K-ε	Turbulent kinetic energy dissipation model
L	Thickness (m)
L	Length
L,V,H,C	Lighting, Ventilation, Heating, Cooling
LRHn	Living Room House Number of case
m^2k/w	Resistance
N	Number of air changes per hour
ºC	Celsius or Centigrade
Q	Heat flow
Qc	Conduction heat gain or loss
Qe	Evaporation heat loss
Qi	Internal heat gain
Qs	Solar heat gain
Qv	Ventilation heat gain or loss
q_v	Ventilation rate (m^3)
R	Thermal resistance (m^2k/w)
RMSPE	Root Mean Square Percent Error
SCHn	Shallow Courtyard House Number of case
SET	Standard Effective Temperature

SPSS	Statistical Package for the Social sciences
T_{air}	Air temperature
$T_{air\ dp}$	Dew point temperature
tc	Temperature of the cold side (°C)
th	Temperature of the hot side (°C)
T_i	Inside air temperature (°C)
Tn	Neutrality Temperature (°C)
T_o	Outside air temperature (°C)
To.av	Average Outside air temperature (°C)
T_{sky}	Sky temperature
U	Heat transfer (w/m²k)
V_g	Mean wind speed reference height Z_g
Vr	Volume room or building (m³)
V_z	Mean wind speed height Z
W	Width
W/M°C	Conductivity (heat flow rate through unit area of unit thickness of substance with unit temperature difference between the two faces)
W/M²K	Heat transfer (heat flow rate through unit area of body with unit difference in temperature of air on the two side)
X,Y,Z	Coordinate directions
YR	Yemeni Riyal
Y_{ta}	Actual values
Y_{tb}	Base simulated values
Z	Height above ground level
Z_g	Reference roughness

APPENDICES

LIST OF PUBLICATIONS & SEMINARS

1. Thabet, M. M., Ismail, A. M and Ismail, M. R. (2006). Analysis of the Thermal Behaviour in the Traditional Courtyard Houses of Yemen. Proceeding of the International Conference on Sustainable Housing (ICSH) 18-19 September, 2006. Malaysia.

2. Thabet, M. M., Ismail, A. M and Ismail, M. R. (2006). Comparison Recording Air Temperature with Computational Fluid Dynamics “FLO*VENT*”. Proceeding of Post—Graduate Research Colloquium 27-28 Feb. 2006, H, B and P. USM. Penang, Malaysia.

TINGKAH-LAKU TERMA DI DALAM RUMAH-RUMAH TRADISI BERLAMAN DALAM DI YEMEN

ABSTRAK

Perkembangan pesat dalam suhu global, populasi, penggunaan tenaga dan pencemaran telah menjadi isu penting yang kian membimbangkan. Isu-isu ini telah memaksa kerajaan Yemen untuk mengurangkan penggunaan tenaga dalam semua sektor khususnya dalam sektor perumahan. Pengurangan penggunaan tenaga memerlukan pengunaan teknik-teknik pasif dan bahan tempatan untuk mengawal perlakuan terma normal seperti mana lazimnya dalam bangunan rekacipta tradisi. Jenis rumah di Yemen berbeza dari kawasan ke kawasan bergantung kepada bahan binaan yang ada, iklim dan teknik pasif pengawalan terma yang khusus untuk setiap kawasan. Kajian ini meneroka teknik-teknik pasif yang diguna pakai oleh rumah-rumah tradisional di kawasan pantai Hadhramout yang panas terik dan berbahang itu. Ciri utama rumah-rumah tradisional di kawasan ini ialah penggunaan ruang legar bertanah liat. Soalselidik juga telah dijalankan di Hadhramout untuk menentukan sikap penghuni terhadap pengurangan penggunaan tenaga melalui penggunaan bahan tempatan dan teknik-teknik pasif kawalan terma. Kajian menunjukkan bahawa kebanyakan responden merasakan bahawa penggunaan teknik kawalan terma semulajadi dan bahan tempatan dalam pembinaan merupakan salah satu cara mengurangkan penggunaan tenaga di Yemen. Menerusi kajian lapangan di kawasan pantai Hadhramout, kajian bermatlamat menyiasat kesan dua nisbah aspek yang berlainan dalam sebuah rumah yakni bagi ruang legar yang cetek dan yang dalam. Keputusan menunjukkan bahawa, pada umumnya, suhu udara adalah kurang di dalam rumah tradisional berbanding dengan persekitaran luar. Perbandingan bacaan suhu udara di dalam ruang legar menunujukkan bahawa tatkala nisbah aspek ruang legar meningkat suhu udara turut meningkat. Data dari lapangan kemudiannya dibandingkan dengan data dari Komputasi Aliran Dinamik (CFD) perisian FloVent. Keputusan menunjukkan bahawa terdapat korelasi yang baik, $r^2=0.85$, di antara model skala yang disimulasi (ramalan) dan model sebenar di lapangan (diukur). Analisa statistik untuk ralat peratus antara nilai yang diukur dan nilai yang diramal dalam semua kes menghasilkan markah, -1.53%. Daripada kerja lapangan dan simulasi komputer, laman tersebut di anggap sebagai teknik penyejukkan yang paling sesuai untuk menangani kesan iklim kawasan pantai di Hadhramout.

THERMAL BEHAVIOR IN THE TRADITIONAL COURTYARD HOUSES OF YEMEN

ABSTRACT

The rapid increases in global air temperature, population, energy consumption and pollution have become vital issues of concern. These issues have compelled the government of Yemen to reduce energy consumption in all sectors especially in the residential sector. To reduce energy consumption requires the use of passive techniques and local material to control natural thermal behavior as was the case in traditionally designed buildings. The types of traditional houses in Yemen vary from region to region, depending on the available material, climate and passive technique of thermal control peculiar to each area. This research explores the passive techniques used by traditional houses in the hot and humid coastal regions of Hadhramout. The main characteristic traditional houses in this area are the use of mud courtyards. A survey was carried out in Hadhramout to determine resident's attitudes about reducing energy consumption through the use of local material and passive techniques of thermal control. The study shows that most respondents felt that the use of natural thermal control technique and local materials in construction constituted one way of reducing energy consumption in Yemen. Through field studies in coastal Hadhramout, the study aims at investigating the effects of two different aspect ratios of courtyards in one house namely that of the shallow and the deep courtyard. The results show that in general there is lower air temperatures in the traditional houses compared to the external air temperature and in some cases the air temperature is within the thermal comfort zone of Hadhramout. Comparing the results of the air temperature within the courtyards indicate that, as the aspect ratio of the courtyard increases the air temperatures also increases. Data collections from field work were then compared with data generated from Computational Fluid Dynamics (CFD) used software FloVent. The results indicate good correlation of r^2=0.85 between the simulation scale model (predicted) and the actual model in the fieldwork (measured). Statistical analyses on the percentage error between the measured and the predicted values in all cases yielded a score of -1.53%. From the fieldwork and computer simulation the courtyard is considered to be the most suitable cooling technique designed to alleviate the effects of the coastal climate of Hadhramout.

CHAPTER ONE

INTRODUCTION

1.1 Background

In the past Yemenis used to live in the same regions that they live in today, with the same climate but without electricity. They also depended on natural resources from their immediate environment to be used as building materials for their houses.

Now large artificial cooling systems such as air-conditioning fed by huge amounts of electricity are used in preference to natural techniques of cooling. Thus, natural resources like oil will be heavily utilized and eventually depleted. In confronting this scenario, Fathy (1986) advises architects "to renew traditional architecture from the moment when it was abandoned; and try to bridge the existing gap in its development by analyzing the element of change and, applying modern techniques to modify the valid methods established by our ancestors, before developing new solutions that satisfy modern needs".

There have been many studies regarding passive thermal control through the use of wind towers and courtyards as natural ventilation devices. Al-Bakri (1997) notes that the two architectural elements used for natural ventilation in traditional houses were the courtyard and the triangular openings which could not be found in a typical modern house. Thus, losing the most important element in the process i.e., the courtyard, will limit the ability of the existing modern houses to apply passive thermal control in the same way as traditional houses do. Nevertheless, there has been no study as yet on the system used in the traditional houses that have two courtyards i.e., the shallow and deep courtyards. The design of these traditional houses that are made of mud is as illustrated in Figure 1.1.

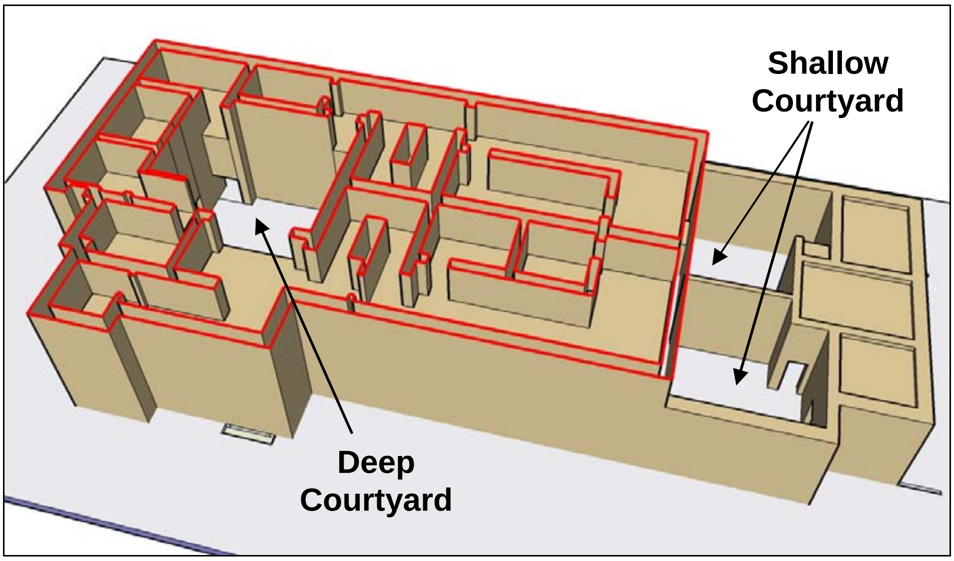


Figure1.1: Model View of Traditional House with Deep and Shallow Courtyards

1.2 Issues and Problem

In the last few years many countries of the world have made repeated calls for the conservation of energy, one of them being Yemen. Before independence, the people in Yemen built their houses according to their real needs in harmony with the environment as well as with extensive and optimal utilization of the available local building materials. In fact, Yemenis endeavored to make full use of nature in the design of their houses. One of which was the extensive use of natural systems in lighting, ventilation, heating and cooling (LVHC).

After independence in 1967, especially after the unification of northern and southern Yemen as the Republic of Yemen in 1990; and the discovery of oil, the country witnessed rapid development in all aspects, particularly in construction (Ahmet, 1994). Factors, such as the return of Yemeni immigrants, in 1991 after the second Gulf war and the influx of the population into cities in search of better incomes, have led to serious problems within the ancient walled cities that dot the Yemeni landscape. Consequently, mass housing projects have been built on city outskirts to relieve some of the pressures on the inner city areas. These new neighborhood projects have been implemented by companies influenced by European architecture and technology, i.e., current designs have used many ideas and building materials from the West without careful consideration for the Yemeni climate (Al-Guhi, 2000).

Houses built in Yemen in the last two decades have given much attention to building regulations but have neglected the climatic aspects and the utilization of local materials. Given this trend, the use of modern mechanical systems in these homes has increased electricity consumption as shown in Figure 1.2.

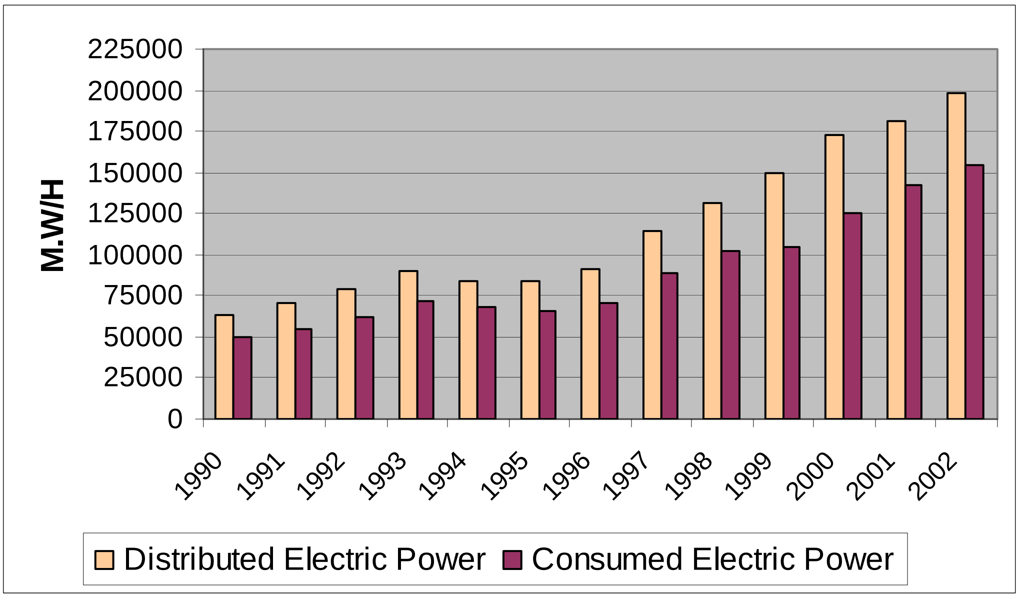


Figure 1.2: Electricity Consumption in Residential of Coastal Hadhramout
Source: Branch Ministry of Electricity in Hadhramout Governorate

This increase in energy consumption inevitably leads to more natural resources (oil) being consumed as shows in Figure1.3: apart from causing air pollution and thus affecting the quality of indoor air. This will not only have harmful effects on the health of households but also influence strategies and plans to promote economic growth in the Republic of Yemen.

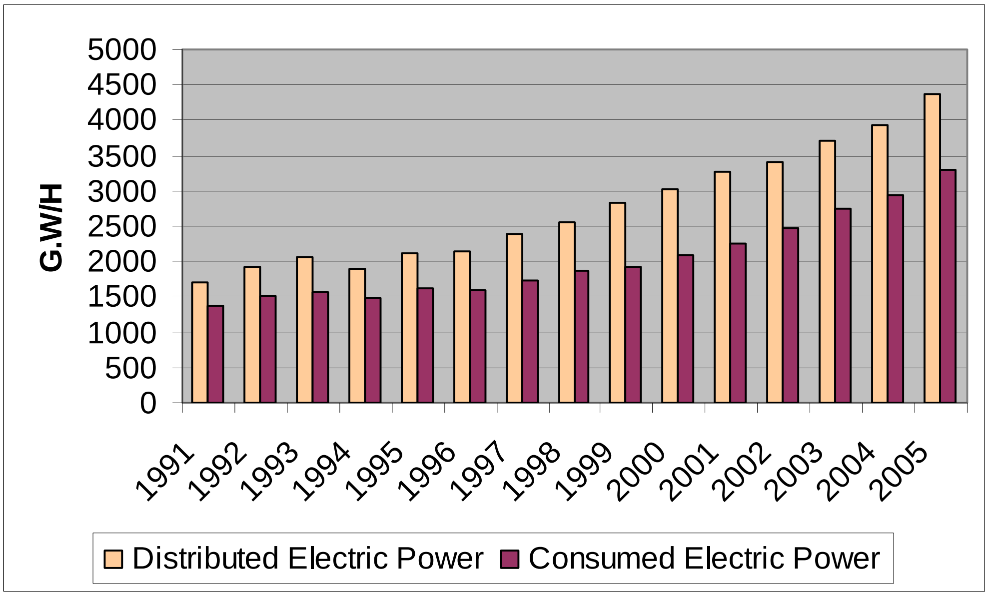


Figure 1.3: Electricity Consumption in Yemen from 1991 to 2005

Source: Central Statistical Organization, Yemen (2005)

1.3 Aim

The main aim of this study is to investigate the natural thermal control in the internal environment of traditional houses in Yemen.

1.4 Objectives

The objectives of this study are:

1. To identify the types of passive design elements present in traditional houses in Yemen.

2. To conduct a questionnaire survey to assess individual attitudes towards the use of passive thermal control so as to reduce energy consumption.
3. To study and investigate the thermal behavior of the traditional courtyard houses and their adjoining spaces (room) from the actual field measurements.
4. To confirm the field measurement results against results from model houses simulated using the computational fluid dynamic (CFD) software FloVent.

1.5 Significant of the Study

This study is initially significance as a knowledge contribution to the field of academic. The study enhances the importance of passive technique applied in the traditional courtyard houses in Yemen. It would give an idea to the Yemeni the effect of courtyards on indoor environment. The study could also benefit the Yemeni's professionals in the construction companies, architects as well as students and other individuals for them to aware and understand the advantages of traditional architecture in Yemen.

1.6 Limitations of the Study

The study was concentrated and limited only to the coastal area of Hadhramout where mud double courtyard houses can be found. Traditional houses in this part of country are formed by a compact layout in which the only open spaces are the inner courtyards. In this region, modern houses with mechanical ventilation systems can be found. Therefore, the study had conducted an inventory in the fieldwork and confirmative data collection between traditional houses and modelled scale houses in the same climatic condition in the coastal area of Hadhramout.

The mud courtyard houses in this area are standard structures. The combination of two courtyards houses in this area and their relationship to the surrounding rooms is the main concern of this study of mud houses.

1.7 Research Question

The research questions of the study are as follows:

1. What are the types of passive design elements present in traditional houses in Hadhramout, Yemen?
2. What is the thermal behavior of the traditional courtyard houses and their adjoining spaces (room) from the actual field measurements?
3. Does the field measurements confirmed against similar measurements from model houses simulated by the FloVent software?
4. What are the individual attitudes towards the use of passive thermal control so as to reduce energy consumption?

1.8 Working Conceptual Model

The chart of a conceptual working model as to recap the general idea of the research explained above. The summary of design guidelines are recommended in this study. The working conceptual model of this the thesis is shown in Figure 1.4.

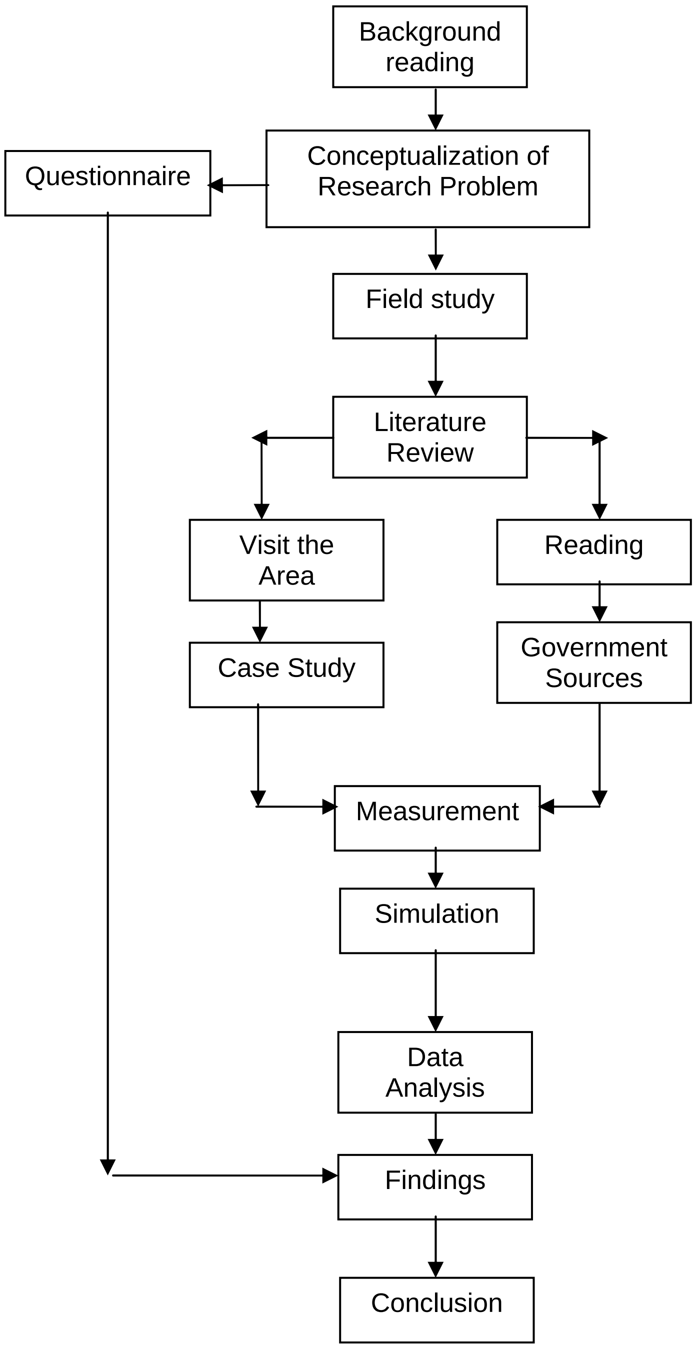


Figure1.4: The Working Conceptual Model

1.9 Outline of Thesis

The thesis is organized into eight chapters. These are summarized as below:

Chapter One: Introduction

The first chapter forms the introduction of the thesis that focuses on the background, problem, aim and objectives of the research, its limitations, research questions as well as the working conceptual model.

Chapter Two: Background Study of Yemen

The second chapter gives information on the Republic of Yemen, its location in Asia, its regions and topography and its climate. This chapter also provides an overview of traditional houses in Yemen, describing the construction and materials of each type of house in each region.

Chapter Three: Thermal Behavior in Houses of Yemen

Chapter three outlines how the orientation system used in the city and in the houses that are suited to its environment and its benefit to the occupants. The theory of thermal behavior in houses and the influence of climate on the design of building are also included.

Chapter Four: Methodology

Chapter four describes the methodology used in this research which includes the questionnaire survey, fieldwork measurement and simulation using a CFD program (FloVent).

Chapter Five: Survey

This chapter discuses a questionnaire survey undertaken in Yemen to assess individual attitudes towards the use of passive thermal control so as to reduce energy consumption.

Chapter Six: Case Study

This chapter describes the analysis of the fieldwork data which was taken in the selected traditional houses to identify the thermal performance in courtyards and living rooms.

Chapter Seven: Simulation

This chapter looks into the use of computational fluid dynamics software to simulate the thermal performance of both traditional and model houses these to confirm the data collected from the fieldwork in chapter five.

Chapter Eight: Conclusion

This is the final part of the research which concludes the overall findings of the research as well as laying down some recommendations for future studies.

CHAPTER TWO

BACKGROUND STUDY OF YEMEN

2.1 Climate and Comfort Zones

2.1.1 Location of Yemen

The Republic of Yemen is located in the southwest of Asia, in the southern part of the Arabian Peninsula. Its neighbors are the Sultanate of Oman in the east and Saudi Arabia to the north. On the western border is the Red Sea while in the south lie the Indian Ocean. Yemen is located between latitude 12° to 20°N and between longitudes 42° to 54°E. The total area of the country is approximately 523,000 km². The southern coast of Yemen extends a distance of more than 1200 km in length while the western coast is about 700 km long. There are numerous islands of Yemen's coast, the biggest of which is Socotra, situated south of Yemen. Figure 2.1 represents the map of Yemen.

Figure 2.1: Location of Yemen in the Arabian Peninsula
Resources: Country profile: Asia

2.1.2 Regions and the Topography of Yemen

Yemen was formed through the multi-combination of trans-formable rocks. The topography varies from high mountains, desert areas, long coastal areas and deep valleys. There is a great difference in elevation as the Yemeni landscape rises from sea level to nearly 3700 m. The nation is divided into five geographical regions i.e. Figure 2.2 shows these regions in Yemen the Coastal region, the Plateau region, the Mountainous region, the Desert region and the Islands. (Statistical Year-Book 2003)

Figure 2.2: Map of Republic of Yemen Showing Each Region
Resources: World Atlas

Geographically Hadhramout governorate is situated between latitude 14° to 20°N and between longitude 47° to 51°E. Hadhramout is situated almost halfway between Aden and eastern borders with Oman. The southern part of the Hadhramout lies on the coastal region covered to the west with sand dunes, the middle part of Hadhramout lies on the plateaus region and the northern part of the Hadhramout lies on the desert region.

The history of Hadhramout as a trading centre dated back over 3000 years. Marco Polo and Ibn Batuta visited Al-Mukalla city in the 11th and 12th centuries. Al-Mukalla was often visited by traders and as a stop over from China and India. In the 1800's Al-Mukalla grew as a ship fuelling port, holding stocks of coal and water supplies for the early steamers.

Al-Mukalla is the capital of Hadhramout governorate now, located off the southeast tip of Yemen and at the south of the Arab Peninsula. Al-Mukalla is one of the Yemeni ports on the Arabian Sea. Fishermen were the first to settle in Al-Mukalla having emigrated from adjacent regions. Al-Mukalla is the capital of the Qua’iti Sultanate in 1877. The economy of Al-Mukalla is based on fishing industry.

2.1.2.1 The Coastal Region

The coastal strip lies between the Red Sea and the Arabian Sea and is 1900 km long. It includes the western plain (Zabid, Rima) and the Southern plain (Ahwar, Hajer and Mayfa'a). The western plain lies between the Red Sea and the Western Escapement with an altitude of up to 300 m. It is 420 km long and has a width of between 20 to 40 km. The southern plain lies between the Arabian Sea and the southern escapement with the altitude rising to about 200 to 500 m high. It is between 10 to 60 km wide.

2.1.2.2 The Plateaus Region

The eastern plateaus are dissected in particular by, the north Hadhramout and its tributaries. The climate in general is hot and dry; with annual rainfall below 10 mm. The eastern plateaus include both low and high mountains ranges. Altitude varies between 1000 m to 1700 m above sea level.

2.1.2.3 The Mountainous Region

The High lands tower up to 1800 m above the plains of Saada and Sana'a. This area lies to the east and north of the mountainous region, which has hills in parallel with the hills facing the Rub Al-Khali (Desert of Empty Quarter). The altitude ranges from 1800 to 3760 m above sea level. The climate varies from hot at lower elevations to cool at the highest altitudes and average rainfall is from 300 to 1000 mm.

2.1.2.4 The Desert Region

The desert region covers large areas of Al-Jawf, Mareb, Shabuwa and part of Hadhramout and elevation drops gradually from 1000 m towards the north east to less than 500 m in the desert. Rainfall and vegetation are nearly absent. In the north, lies the Empty Quarter Desert (Rub’ Al-Khali), which extends into Saudi Arabia and is approximately 500,000 km^2 in area. This sandy desert is one of the most desolate regions of the world.

2.1.2.5 The Islands

The Republic of Yemen has more than 120 islands. The most important of all is Socotra with its unique biodiversity of flora and fauna unlike that of any other region in Yemen. Socotra is the biggest island in Yemen. It is situated south of Yemen and has an area of 3100 km².

The physical and geographical barriers of high mountains, large deserts, deep valleys and extensive coastal areas have naturally divided the country into three urban zones. Each zone has a different climate and traditional heritage. The zones are: the Coastal Region, the Plateau Region and the Mountainous Region. (Leipzig, 1996)

2.1.3 General Climate of Yemen

The climate in Yemen varies according to its different topography. The country could be divided into three urbanized zones, each of which has very different climatic conditions. There are no distinct variations between the seasons. Generally, there are two main seasons, namely, summer and winter. The climate of the coastal region during the summer is hot with the air temperature of about 35 °C and humidity as high as 80 %. The mean temperature in winter is around 22 °C. The average annual rainfall varies from less than 50 mm to 255 mm. The coastal region includes the low coastal plains facing the Red Sea, the Gulf of Aden and the Arabian Sea. It consist a coastal strip extending from the Omani border in the east towards the Gulf of Aden in the southwest and towards the Saudi border in the north.

The plateau region covers the northern boundary of Yemen. The mountains zone to the west, the coastal plains to the south and the Empty Quarter desert to the north border of this region. The climate here is generally whether air temperature at about 32 °C and humidity at about 30 %. The average rainfall in this region is generally below 200 mm. This region is subdivided into the northern zone, the southern zone, Hadhramout and the Al-Ghadydah basin. It contains basin expanses of sand desert and dissected plateaus with altitudes ranging from 500 m to 800 m in the north and south.

The Mountainous region of this area consists of the western mountain range that dominates a large part of the country. Elevation rises from 500 m at the foothills at its southern sections to 3700 m in the western section. Rainfall is related to elevation and generally ranges between 300 - 1000mm. This region is divided into three main catchments zones i.e., the western zone sloping towards the Red Sea, the southern zone sloping towards the Gulf of Aden and the north eastern zone sloping towards the desert of Empty Quarter. Temperate is moderate in summer 24.7 °C and cool in winter 4.6 °C. Tables 2.1 to 2.5 show the air temperatures, wind direction, rainfall and sun path in the major cities of all regions. The location of these major cities is shown in Figure 2.3. These tables provide details of the maximum and minimum temperatures, the angle of the sun, the mean speed and direction of wind during each month as well as monthly rainfall levels.

Figure 2.3: Map of Governorates in Yemen
Resources: World Atlas

Table 2.1: Temperatures and Rainfall at Different Altitude

Zone	Altitude	Mean min - max Temperature ºC	Relative Humidity %	Rainfall mm
Coastal region	<500	22 - 35	80	50
Mountain region	>1700	4.6 - 24.7	50	260
plateau region	1000.1700	18 - 32	30	400

Resources: Leipzig, Yemen (1996)

Table 2.2: Minimum, Maximum and Mean Temperature ºC

City	Sanaa			Aden			Taizz			Al-Mukalla			Socotra Island		
Month	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Jan	26.7	-2.5	12.9	30.7	17.6	25.4	27	6.2	16.7	32.2	13	22.5	28.4	17.6	23.7
Feb	29.8	-1.8	16.5	29.5	16.8	24.9	32.6	6.4	19	30.7	11.8	22	29.5	17	23.1
Mar	28.6	6	17.4	31.2	22.6	27.1	31.8	10.8	20.9	31.7	14.3	24.4	31.7	15.2	25.2
Apr	30	6.8	19.5	33.4	21	28.6	34.6	13	23.1	34.4	15.4	26.2	37	20.3	27.6
May	31	11.4	21.9	41.8	25.2	31.8	35.2	15	24.1	36.8	24.8	30.4	37.7	23.7	30.7
Jun	32	12	22.7	40.5	26.1	32.5	37	17	25.5	36	23.2	30.7	35.6	25.2	29.6
Jul	33.1	13	23.2	38.7	24	31.8	35.5	15	24.7	34.6	21.8	29.6	35.5	22.5	28.1
Aug	32.1	12.5	22.4	39.5	26.9	32	34	14.6	23.8	35	21.6	29	34	22	27.9
Sep	31	9.6	21	38.2	24.7	30.9	34.5	12.4	22.9	34.3	22.8	28.8	34.8	22.6	28.9
Oct	28	5.4	18	35.2	23.6	29.5	33	12.6	22.1	33.4	20.6	28.3	33.5	21.5	27.1
Nov	26	2	14.4	33.6	20.4	26.7	31.6	9.4	19	34.2	16.8	25.8	32.4	18	25.5
Dec	28.2	1.5	14.8	32.2	21	26.5	29.4	10	18.7	31.5	19.5	25.6	30.3	20	25.9
Mean	29.7	6.3	18.7	35.4	22.5	28.9	33.0	11.9	21.7	33.7	18.8	26.9	33.4	20.5	28.5

Resources: Statistical Year-Book (2003)

Table 2.3: The Angles of the Sun in Summer and Winter over the Major Cites of Yemen.

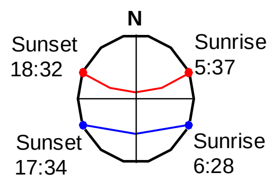
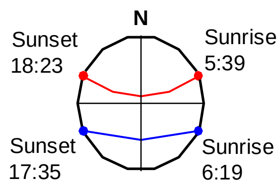
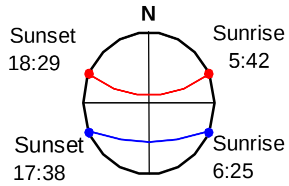
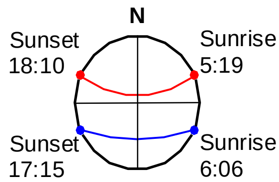
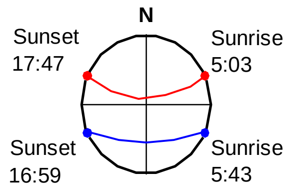
<table>
<tr><th>City</th><th>Latitude</th><th>Longitude</th><th>Solar Azimuth</th><th>Day Month</th><th>Solar Position</th></tr>
<tr><td rowspan="2">Sana'a</td><td rowspan="2">15.3º N</td><td rowspan="2">44.1º E</td><td>65.65º</td><td>21 Jun</td><td rowspan="2"></td></tr>
<tr><td>114.39º</td><td>21 Dec</td></tr>
<tr><td rowspan="2">Aden</td><td rowspan="2">12.5º N</td><td rowspan="2">45º E</td><td>65.96º</td><td>21 Jun</td><td rowspan="2"></td></tr>
<tr><td>114.08º</td><td>21 Dec</td></tr>
<tr><td rowspan="2">Taez</td><td rowspan="2">13.3º N</td><td rowspan="2">44º E</td><td>65.88º</td><td>21 Jun</td><td rowspan="2"></td></tr>
<tr><td>114.16º</td><td>21 Dec</td></tr>
<tr><td rowspan="2">Al-Mukalla</td><td rowspan="2">14.5º N</td><td rowspan="2">49.2º E</td><td>65.74º</td><td>21 Jun</td><td rowspan="2"></td></tr>
<tr><td>114.3º</td><td>21 Dec</td></tr>
<tr><td rowspan="2">Socotra Island</td><td rowspan="2">12.5º N</td><td rowspan="2">54º E</td><td>65.96º</td><td>21 Jun</td><td rowspan="2"></td></tr>
<tr><td>114.08º</td><td>21 Dec</td></tr>
</table>

Table 2.4: Wind Speed and Directions

City	Sanaa		Aden		Taizz		Al-Mukalla		Socotra Island	
Month	m/s	Direction	m/s	Direction	m/s	Direction	m/s	Direction	m/s	Direction
Jan	4.9	N	4.4	E	3.2	S	4	SE	8.7	E
Feb	4.8	N	4.9	E	3.4	S	3.9	SE	8.2	E
Mar	5	SW	5.8	E	3.8	S	4.2	SE	6.3	NE
Apr	4.2	NE	4.8	E	3.6	S	4.2	SE	5.2	NE
May	4.6	NE	3.8	E	3.3	W	4.1	SE	7.4	S
Jun	4.9	N	3.2	SE	4.7	NW	3.7	SE	12.7	S
Jul	5.9	W	4.7	SW	5.4	NW	3.6	SE	14	S
Aug	4.5	N	6.7	SW	5.3	NW	3.4	SE	13.2	S
Sep	4.9	NE	4.9	SE	3.8	S	3.8	E	8.7	S
Oct	4.3	NE	4.4	E	4.2	S	3.9	E	5.8	NE
Nov	4.5	N	5.6	SE	4.2	S	3.8	SE	4.9	NE
Dec	9.1	N	6	E	4.2	S	4.8	SE	6.5	NE
Mean	5.1	-	4.9	-	4.1	-	3.9	-	8.5	-

Resources: Statistical Year-Book (2003)

Table 2.5: Rainfall (mm)

City / Month	Sanaa	Aden	Taizz	Al-Mukalla	Socotra Island
Jan	0	3.1	0	0	14.6
Feb	0.7	0	0	0	0
Mar	95.7	0	74.3	0	0.5
Apr	24.9	0	32.2	0	0
May	5.9	4.5	233.4	0	4.4
Jun	0	0	90	0	0
Jul	96.6	0	138.6	0	0
Aug	74.6	6.3	107.3	0	0
Sep	3.4	0	101.2	4.2	7.3
Oct	0	0	32.5	0	18.8
Nov	0	0	0	0	0
Dec	0.4	0	1.4	8.3	7
Total	302.2	13.9	810.9	12.5	52.6

Resources: Statistical Year-Book (2003)

2.1.4 Climate in Hadhramout

The climate in Hadhramout is hot and humid in summer and moderate in winter. Temperatures reach 40 °C in the plateau region, where a dry tropical climate prevails. In coastal region, the temperature is 36 °C due to high humidity of 80 %. In the winter temperature tends to be moderate, between 20 °C to 24 °C in the coastal region and 17 °C to 20 °C in the plateau region.

2.1.4.1 Sunshine and Solar Radiation

The sun is the source of all forms of energy on earth and is the fundamental source of global weather patterns. It is also the most important element for heat gains in a building as its orientation and global position will determine a building's exposure to solar heat. The city of Al-Mukalla is located in the coastal region, at an altitude of 14° 5′ north and a longitude of 49° 20′ east. The Sun Path Diagram for given latitude can be used to determine the sun's position in terms of altitude and azimuth for any hour of the year.

The Sun Path diagram for the city of Al-Mukalla is presented in Table 2.3. This table shows the position of sun in the summer months as of June 21 and in the winter months as of December 21. Based on its location, Al-Mukalla receives 8 to 10 hours of sunshine for eight months from October to May and 5 to 6 hours during the remaining four months. It should be noted that solar radiation intensity is closely related to the duration of sunshine hours.

2.1.4.2 Temperature

As coastal Hadhramout is bordered by the eastern plateau in the north and the Arabian Sea in the south, with no lakes or rivers, its local day temperatures tend to be high with a very high humidity. In the summer months, the day temperature reaches 40 °C and the relative humidity may increase to more than 90 %. The air temperature and relative humidity values from 1999 to 2004 are plotted in Figures 2.4, 2.5 and 2.6.

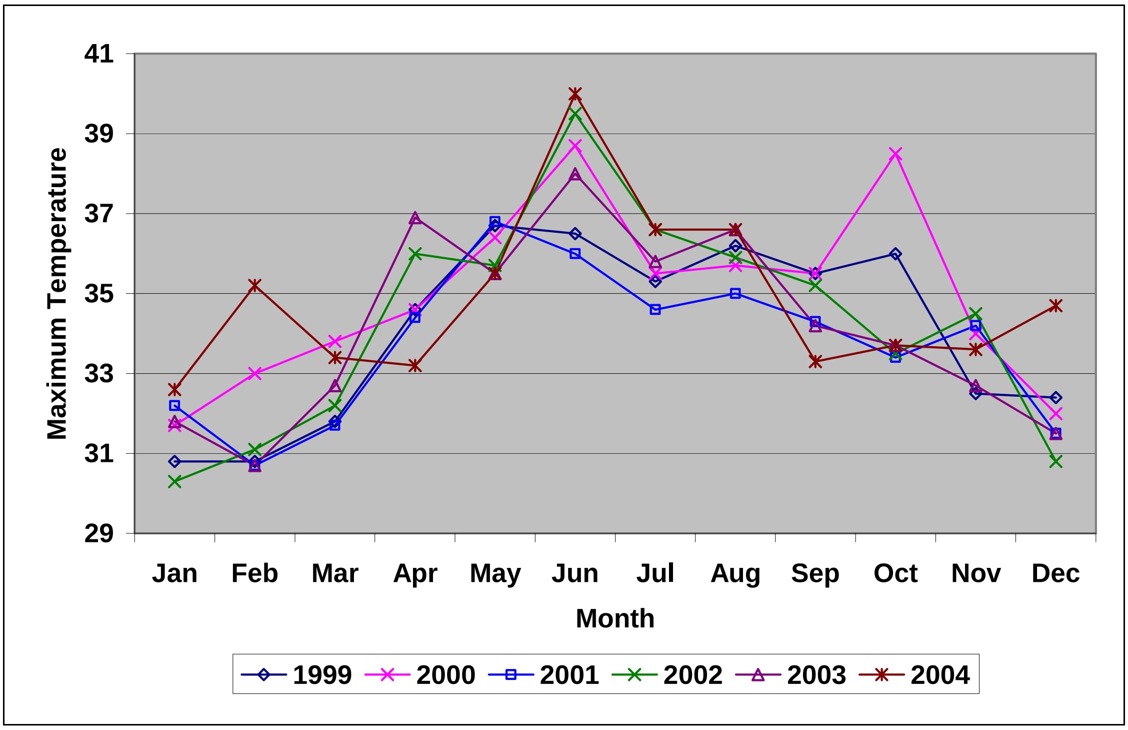


Figure 2.4: Maximum Daily Temperatures for Al-Mukalla City
Resources: Statistical Year-Book (1999-2004)

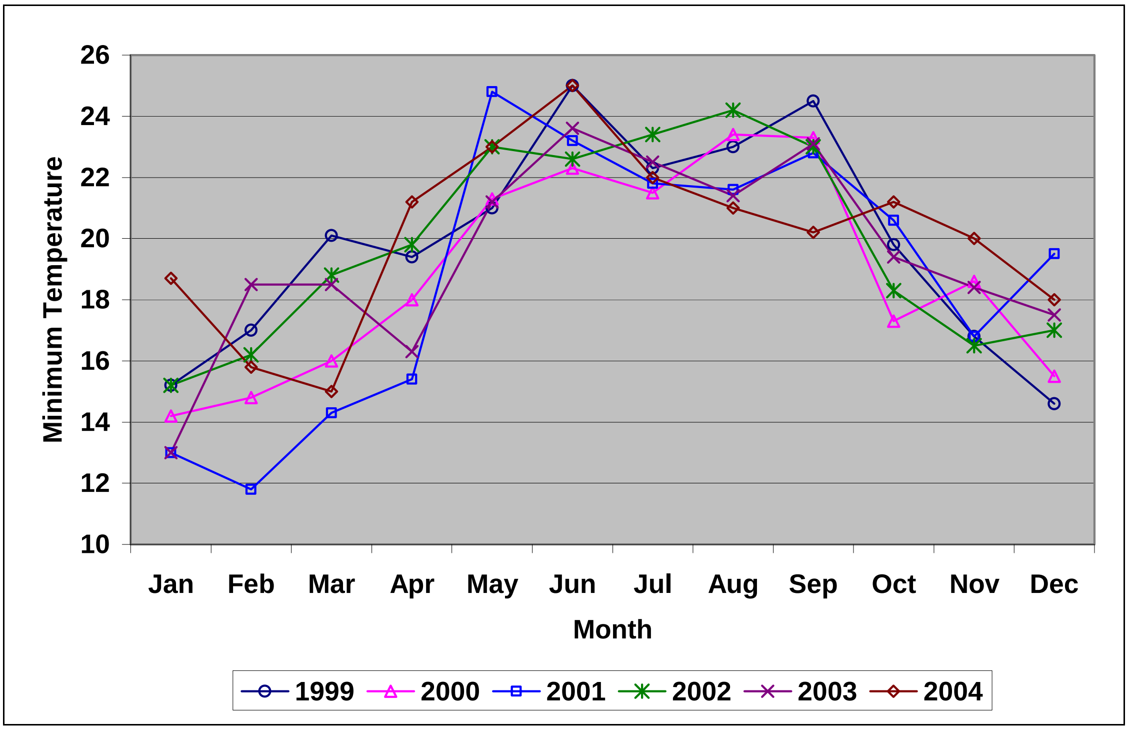


Figure 2.5: Minimum Daily Temperatures for Al-Mukalla City
Resources: Statistical Year-Book (1999-2004)

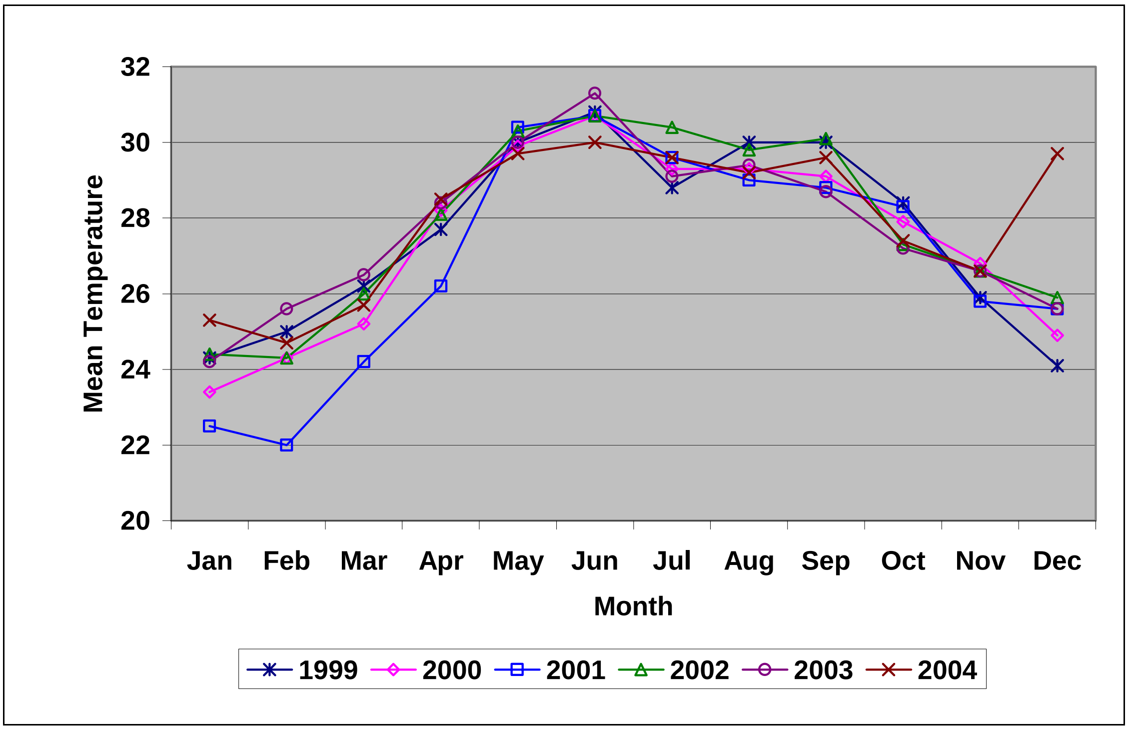


Figure 2.6: Mean Daily Temperatures for Al-Mukalla City
Resources: Statistical Year-Book (1999-2004)

2.1.4.3 Relative Humidity

Almost all regions in Yemen are situated at a considerable height above sea level. Thus relative humidity generally varies from region to region on a monthly basis except for the coastal region where high relative humidity is common. The mean monthly relative humidity in coastal Hadhramout is about 60 to 80 % Figure 2.7. In the most humid month, relative humidity ranges between 78 to 82 %. Generally in this region, humidity increases in April just before the southwest monsoon starts and drops in the cooler months of November and December. The relative humidity is normally at its minimum values from November to January and at its maximum values from May to September. Therefore, the summer weather in the coastal region can be considered to be very hot.

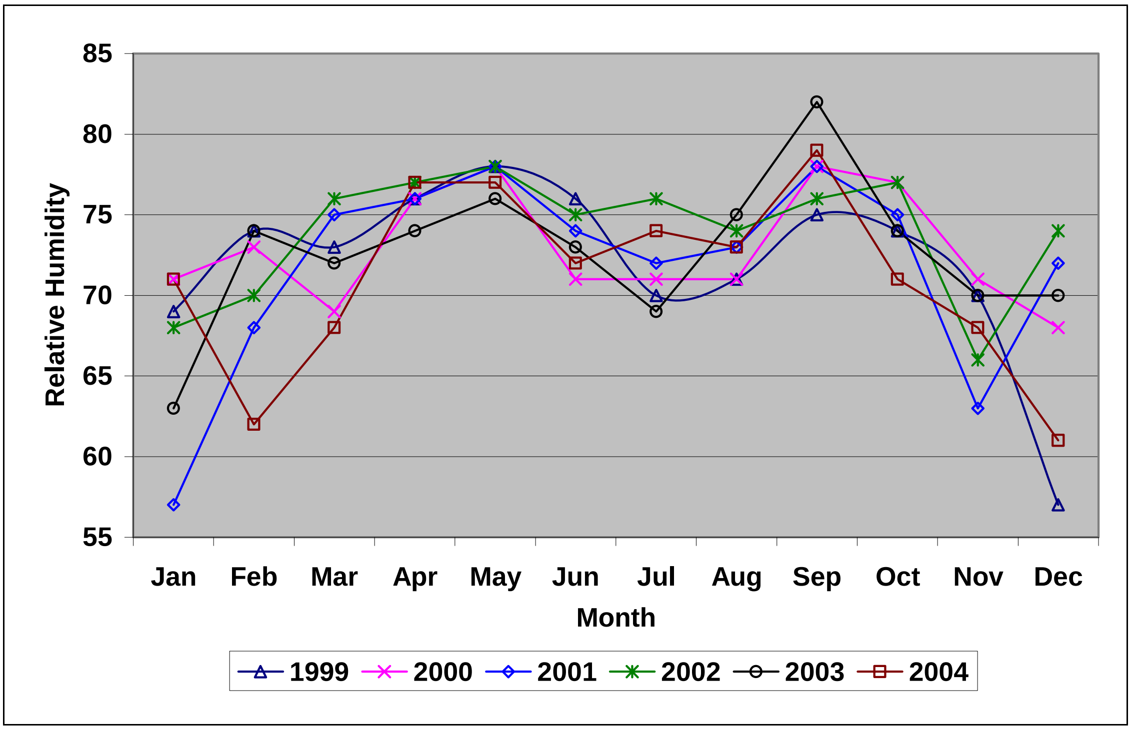


Figure 2.7: Mean Relative Humidity for Al-Mukalla City
Resources: Statistical Year-Book (1999-2004)

2.1.4.4 Wind

Wind speed is used to control thermal comfort but it is a very unstable parameter. The direction of wind constantly fluctuates due to driving sand storms and dust or rain in the region. Generally, the wind direction is dictated by temperature differences during daytime and nighttime. The prevailing wind directions in coastal Hadhramout are southeast with speeds of between 2 to 4 m/s. From Table 2.6, it is clear that most of the wind in Al-Mukalla throughout the year comes from the southeast direction.

Table 2.6: Wind Speed and Directions in Al-Mukalla City

Wind	1999		2000		2001		2002		2003	
Month	**m/s**	**Dir-n**	**m/s**	**Dir-n**	**m/s**	**Dir-n**	**m/s**	**Dir-n**	**m/s**	**Dir-n**
Jan	2.7	SE	2.2	SE	4.1	SE	4.5	SE	4.8	SE
Feb	2.8	SE	2.3	SE	3.9	SE	4.7	SE	4.6	SE
Mar	2.5	SE	2.3	SE	4.2	SE	4.6	SE	4.6	SE
Apr	2.4	SE	2.5	SE	4.2	SE	4.3	SE	4.6	SE
May	2.5	E	2.5	SE	4.1	SE	4	SE	4.5	SE
Jun	3.1	SE	2.8	SE	3.7	SE	3.9	SE	4.7	S
Jul	3.6	SW	3.3	SW	3.6	SE	4.5	SE	4.8	S
Aug	4.1	SE	3.6	SE	3.4	SE	3.5	E	4.1	SE
Sep	3.8	NE	2.4	E	3.8	E	4.6	SE	3.4	E
Oct	2.5	SE	2.2	SE	3.9	E	4.3	SE	4.6	SE
Nov	2	SE	2.2	SE	3.8	SE	4.3	SE	4.6	SE
Dec	2.7	SE	2.2	SE	4.8	SE	3.5	E	4.8	SE
Mean	2.9	-	2.5	-	3.9	-	4.2	-	4.5	-

Resources: Statistical Year-Book (1999-2003)

2.1.4.5 Precipitation

There are two rainy seasons in the coastal region of Hadhramout. The first is during February, March and May, and the second stretching from September to November. The average annual rainfall varies from less than 12.5 mm in the coastal areas of Yemen to 2 mm in the desert of Empty Quarter. Rain is very scarce in the Empty Quarter desert, which is located in the north of Hadhramout. Rainfall in any region could influence the design of houses especially the shape of their roofs. Generally, houses in Hadhramout use flat roofs which are suitable in low rainfall conditions. Table 2.7 shows the quantity of monthly rainfall (mm) in Al-Mukalla from 1999 to 2003.

Table 2.7: Rainfall (mm) in Al-Mukalla City from 1999 to 2003.

	1999	2000	2001	2002	2003
Jan	0	0	0	1	0
Feb	5.3	0	0	4.1	1
Mar	0.4	0	0	7.8	0
Apr	0	0	0	63	0
May	11.8	0.5	0	0	0
Jun	0	0	0	0	0
Jul	0	0	0	0.2	0
Aug	0	0	0	0.1	1.2
Sep	0	0	4.2	0	0
Oct	1	5	0	0	0
Nov	0	11.5	0	0	0.2
Dec	0	1	8.3	9	1.1
Total	18.5	18	12.5	85.2	3.4
Mean	1.5	1.5	1.0	7.1	0.3

Resources: Statistical Year-Book (1999-2003)

2.1.5 Thermal Comfort Requirements

The Yemeni external climate can be summarised as being hot and humid in the coastal area and hot and dry in the highlands. In order to design a proper passive system, it is important to know the Yemenis thermal comfort expectation. Sayigh (1998) argued that thermal comfort depends the mind's attitude towards the environment. The comfort zone is defined as the range of climate conditions within which the majority of people would not feel thermal discomfort, either hot or cold. Koenigsberger *et al*. (1974) observed that a comfort zone varies from individual to another depending on age, sex, clothing worn, type of activity performed and geographical location.

Figure 2.8 shows the monthly daily average mean dry bulb temperature and relative humidity readings for 10 years (1980 - 1990) in Al-Mukalla (Meteorological Service). The monthly lines on the chart show that only 6 months cross the ASHRAE standard comfort zone. In other words, the monthly