VENTILATION AND COOLING
18TH AIVC CONFERENCE, ATHENS, GREECE
23-26 SEPTEMBER, 1997

Title: Natural Ventilation of the Contact Theatre

Author(s): P J Jones*, D K Alexander*, H G Jenkins*, A Short**

Affiliation: *Welsh School of Architecture, Cardiff, UK
** Short Ford Associates, London, UK

Extended Abstract
This paper will describe the design and development of the natural ventilation system of the new Contact Theatre Complex designed by A.Goldrick of Short Ford Associates, now beginning construction in Manchester,UK.

The ventilation design is based on a stack dominant system using an 'H-Pot' chimney configuration. The paper describes the development of the design of both the studio theatre and main auditorium ventilation systems. These have been developed with feedback from wind tunnel and CFD testing so as to produce a strategy and design relatively insensitive to wind direction, yet providing sufficient ventilation to overcome the high heat gains expected from an audience and stage lighting. The potential for conflicts between wind and buoyancy forces have been reduced through the location and positioning of inlets and through the sizing and termination design of the stack.

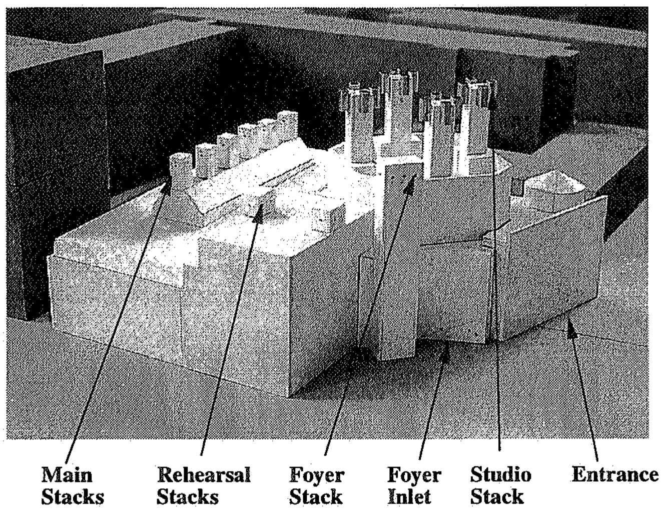


Figure 1 Wind Tunnel model of Contact Theatre initial design.

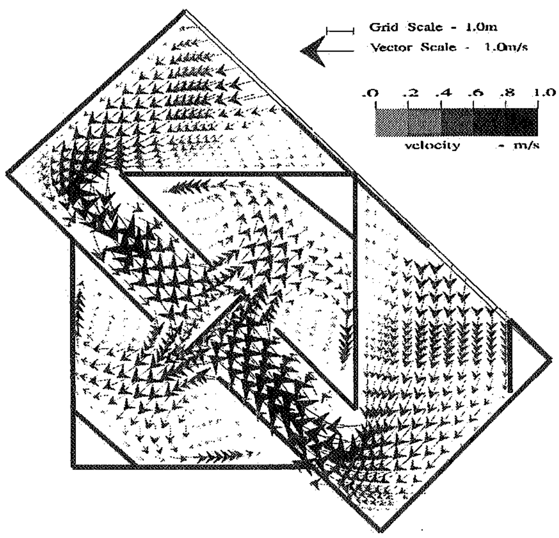


Figure 2 CFD analysis of airflows within mixing chamber beneath Studio theatre.

VENTILATION AND COOLING

18TH ANNUAL AIVC CONFERENCE
ATHENS, GREECE, 23-26 SEPTEMBER, 1997

NATURAL VENTILATION AND THE ROLE OF PASSIVE STACK CHIMNEYS IN TRADITIONAL EXCAVATED AND SURFACE DWELLINGS IN SANTORINI

K. TSIKOURIS and A. YOUNG

THE BARTLETT SCHOOL OF GRADUATE STUDIES
UNIVERSITY COLLEGE LONDON

NATURAL VENTILATION AND THE ROLE OF PASSIVE STACK CHIMNEYS IN TRADITIONAL EXCAVATED AND SURFACE DWELLINGS IN SANTORINI, GREECE

K. TSIKOURIS and A. YOUNG

1. Synopsis

This paper considers the role of passive stack chimneys in controlling indoor thermal conditions in the vernacular houses on the volcanic island of Santorini . The quality of the environment within these dwellings is disputable, mainly because of the high humidity levels. A monitoring study was carried out in four actual dwellings in Santorini, two built on the surface and two excavated into the soft volcanic rock.. The temperature and relative humidity of their main space and their chimneys were monitored and compared to the simultaneous external conditions.

The results of this study were then used in a computer simulation package, modelling the performance of the dwellings and the chimneys in terms of air movement and air change rates. This showed that in most cases, chimneys proved to be efficient, establishing continuous air movement if located correctly, i.e. in the space where ventilation is mostly needed. The air flow characteristics of the chimneys seemed to be based on a diurnal cycle related to the external temperature fluctuation, but with a time lag.

By designing a chimney carefully and using the materials in an appropriate way, the ventilation problems of these dwellings can be solved at low cost, both in terms of running costs and energy consumption. In the last few years, natural ventilation has been adopted by many European designers, as the importance of energy conservation is increasingly realized. The study of the role of passive stack chimneys in natural ventilation can not only be useful for the restoration of such vernacular dwellings, but can also be used in the design of new, environmentally friendly, buildings.

2. The Indoor Environment of Dwellings in Santorini

2.1 Introduction

The volcanic island of Santorini belongs to the Cyclades, a cluster of over thirty islands in the Greek archipelago in the Aegean. Since the old geological periods, Santorini has been shaken by the explosions of the adjacent volcano, as well as by earthquakes, the most recent and destructive being the one that occured on the 9th of July 1956. The volcanic materials are visible everywhere and their presence has dominated the lives of the people, the agriculture and the architecture of the island. The volcanic rock which covers the entire island provides a firm and stable, yet easily worked, material for excavating dwellings that will not collapse, and also provides building blocks for surface dwellings. The uncommon landsacpe of Santorini was favourable to the development of a local architecture of extreme singularity, with excavated dwellings being the basic means of housing. A narrow facade and an elongated vault is the typical and most common layout of most of the excavated dwellings and indeed some of the surface ones.

2.2 The Potential of Natural Ventilation and the Role of Chimneys

An excavated dwelling is substantially a cave. It is surrounded by ground, which provides a huge thermal mass with an astonishing thermal capacity. Therefore this heavy construction has a thermal behaviour which is favourable to the dwelling with regard to temperature. Heat is absorbed by the ground during the hot days and given back at the cooler night-time, maintaining a stable temperature inside, pleasant in the summer and usually in winter, too. But the main disadvantage of an excavated dwelling is the poor air quality and lighting indoors. Since the building is surrounded by ground on all sides but the front, the later is the only way through to the outside air. Openings can only be situated at this front, normally narrow, facade. Daylight penetrates as deep as the first room of the house. Any space situated at the back of the house is hardly ever reached by any daylight at all.

Things get even worse when it comes to natural ventilation. Single-sided ventilation would only be adequate for a depth of up to 5 or 6 m. But excavated dwellings are usually much deeper than this and only the front room has proper ventilation. Since the planning is deep and cross-ventilation is impossible, the spaces at the rear of the house do not usually have any ventilation at all. The air in these spaces changes rarely. Excess moisture remains in the room and, consequently, extremely high relative humidities occur, as the temperature is most of the time kept at low levels. As a result, dampness, odours, mould grouth and condensation on the wall surfaces are common in excavated buildings.

The most common technique applied to assist natural ventilation was the chimney. The operation of a chimney is based on the stack effect. The air tends to move from a space with a high temperature to one with a lower temperature. In cold climates, where the chimneys are used exclusively for the removal of the (hot) smoke to the (cold) outside air, this means that there is a continuous air outflow from the chimney, via an upward air movement. In hot climates like the one of Santorini, where the chimneys also play the role of a ventilation opening in summertime, the flow of the air within the chimney may change direction depending on the various differences between the inside and outside temperatures.

The direction and speed of the wind also affect the performance of a chimney. The wind pressure at the top of the chimney is always negative and, therefore, if the temperature difference is very small, can produce an outflow at the top of the chimney irrespective of any stack effect which may want to drive the flow in the opposite direction. The construction, the shape and the orientation of the chimney determine its performance, as they relate closely to the effect of temperature and wind. Chimneys in excavated buildings in Santorini have a large thermal mass which is provided by the surrounding ground and respond very slowly to the changes of the external conditions. This time lag is expected to create large air temperature differences between the chimney, the external and the internal spaces of the house, which can be favourable to the ideal ventilation performance of the chimney.

A decisive factor for the efficiency of a chimney and its contribution to the natural ventilation of the house is the location within the building. Chimneys located in small isolated rooms are not likely to play an important role in the ventilation, since the air flow to the rest of the house is obstructed. Chimneys near large openings at the front of the house are also expected to be problematic, because the air moving in or out through the chimney will be expelled or drawn in through the front openings without ventilating the rest of the dwelling. Chimneys built at the back of the house or attached to the main room should prove more effective and contribute to the overall ventilation, because they will introduce an alternative to cross ventilation and create air draughts at the rear.

3. The Monitoring Study

3.1 Methodology

In order to demonstrate the effectiveness of chimneys as a means of natural ventilation an experimental study was carried out. Four buildings were selected for monitoring in terms of their environmental conditions. "Smart Reader"[1] data loggers were used, together with the "Trend Reader" [9] software package to record and download readings for temperature and relative humidity. Monitoring took place for one week. For each of the four buildings a data logger was positioned in the middle of the height of the chimney and another was hung in the internal space, at head height. Another logger for monitoring the external conditions, was positioned so that it was always in shade. The location of the loggers in each building is shown on the floor plans (fig. 1-4).

The temperatures obtained were used as input values to the natural ventilation computer simulation program, BREEZE, (Produced by the UK Building Research Establishment) [2] which was used to predict air flow rates in the chimneys and air change rates for the various spaces in the dwellings. The results were used as an interpretative tool to explain the operation of the chimneys and to determine the overall effectiveness of the natural ventilation in these dwellings.

3.2 The Four Case Study Buildings

Four buildings were selected for study from the many traditional buildings on the island, see figures 1 to 4, and were representative of the basic types to be found. They have all maintained their original layout with almost no damage or alteration to the original materials and architectural elements. An original chimney exists in every one of the selected buildings, without any significant change to its initial shape and materials. Buildings 1 and 2 are excavated into the ground whereas 3 and 4 are surface buildings.

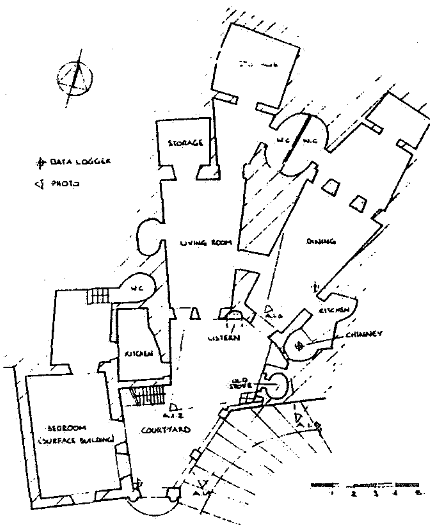


Fig. 1 Building 1: Floor Plan

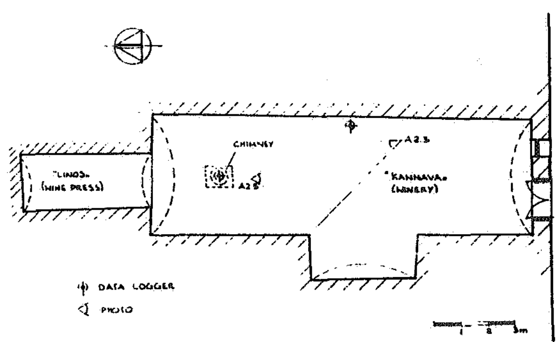


Fig. 2 Building 2: Floor Plan

[1] Smart Reader and Trend Reader are registered trademarks of Status Instruments LTD

In building 1 the chimney is round and has been built in the kitchen above the stove (fig. 1). Half of it is excavated from the ground. When reaching the surface it forms a part of the adjacent public stair's parapet. The rear space of the house is not ventilated at all. In building 2 the chimney is actually a 60cm diameter hole on the roof, which brings light and fresh air into the deep-plan excavated space (fig. 2). Considering that the roof is in reality the ground above, the chimney is a 2.7m high excavated cylinder. The chimney in building 3 is partially excavated, with its main body built on the surface of the ground (fig. 3). In building 4 the chimney is located at the rear of the house, in the room which was probably initially a kitchen (fig. 4). It has an open top and the blowing winds (regardless of their direction) create a negative pressure and support an air movement in the chimney, even when the difference between the external and internal temperature is very low.

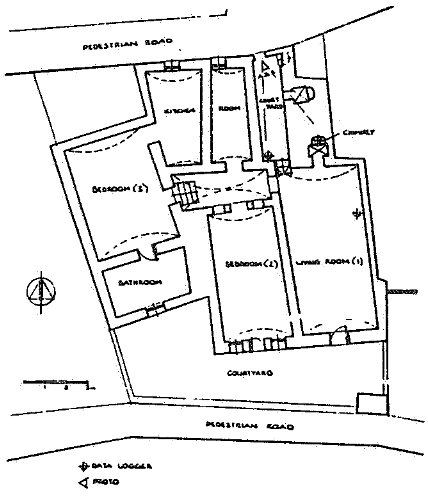


Fig. 3 Building 3: Floor Plan

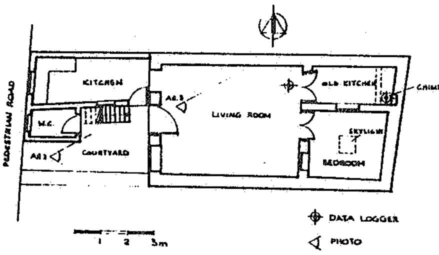


Fig. 4 Building 4: Floor Plan

3.3 Results and Discussion

A summary of the results of the monitoring procedure is presented in Table 1 and sample graphs representing the monitored conditions in building 3 are given in Charts 1-2. In all cases the internal temperature is very stable, at relatively low levels, primarily due to the high thermal mass of the surrounding ground, or the thick walls (in the case of the surface dwellings) which are made of lava rock. The solar and internal heat gains are absorbed by the thermal mass at daytime and given back during the night, when the ambient temperature is lower.

The internal relative humidity is also relatively stable compared to the external one, although it follows the fluctuation of the external conditions by a time lag and it is very common for it to reach very high figures, see Chart 2. The monitored values for relative humidity and temperature for the four buildings were converted to absolute moisture content values, with the use of the equations suggested in [6]. Chart 3 shows the calculated moisture content for the external air and the internal ambient air for building 3, where it can be seen that the moisture content inside is at all times greater than the simultaneous moisture content outside but shows similar trend. This would seem to indicate that the moisture content inside is not determined purely by infiltration and natural ventilation from outside. In Building 3 it appears that other major sources are affecting the moisture content, such as moisture absorption and release from the walls, which could be significant due to the high porosity of the volcanic material of which the building is constructed. However, the plot of moisture content values for building 4 (Chart 4) shows that the moisture content of the external and the internal air are not very different. In this case the moisture content inside is governed by the one outside. Natural ventilation is therefore probably more effective in Building 4, which could be attributed to the position of the chimney (at the rear space of the house).

		EXTERNAL				INTERNAL				CHIMNEY			
		Min	Mean	Max	Range	Min	Mean	Max	Range	Min	Mean	Max	Range
Building 1	Temp. (°C)	22.3	30.3	42.0	19.7	24.1	25.9	29.9	5.8	27.0	29.9	41.1	14.1
	R.H. (%)	16.3	38.0	78.0	61.7	37.1	54.2	64.6	27.5	33.2	46.8	70.9	37.7
Building 2	Temp. (°C)	22.3	30.3	42.0	19.7	22.0	23.8	26.3	4.3	22.0	25.0	29.2	7.2
	R.H. (%)	16.3	38.0	78.0	61.7	50.0	69.0	77.6	27.6	41.4	62.9	78.3	36.9
Building 3	Temp. (°C)	21.6	27.3	37.3	15.7	23.7	24.6	25.5	1.8	22.3	26.2	29.9	7.6
	R.H. (%)	20.7	48.5	86.9	66.2	58.2	73.6	80.4	22.2	30.6	60.4	87.3	56.7
Building 4	Temp. (°C)	21.6	27.3	37.3	15.7	26.2	27.0	28.0	1.8	23.4	27.6	34.9	11.5
	R.H. (%)	20.7	48.5	86.9	66.2	33.9	47.6	58.9	25.0	19.1	42.9	68.8	49.7

Table 1: Monitored Conditions for the four Buildings

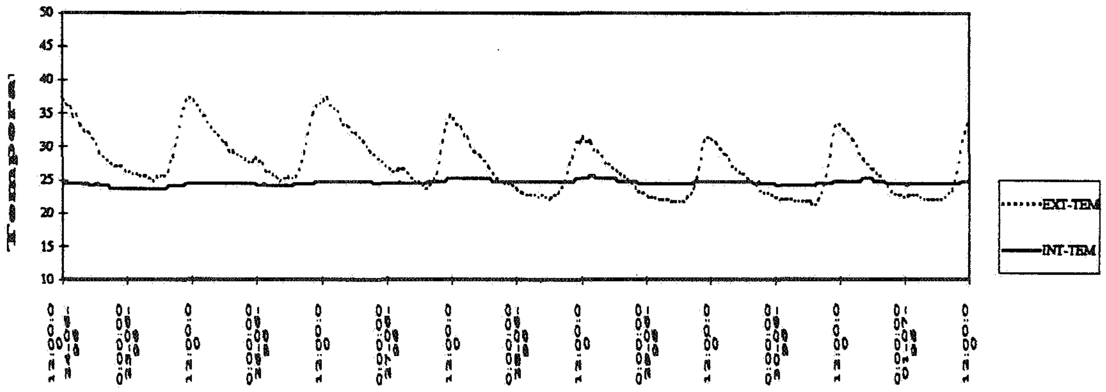


Chart 1: Building 3 - Temperature

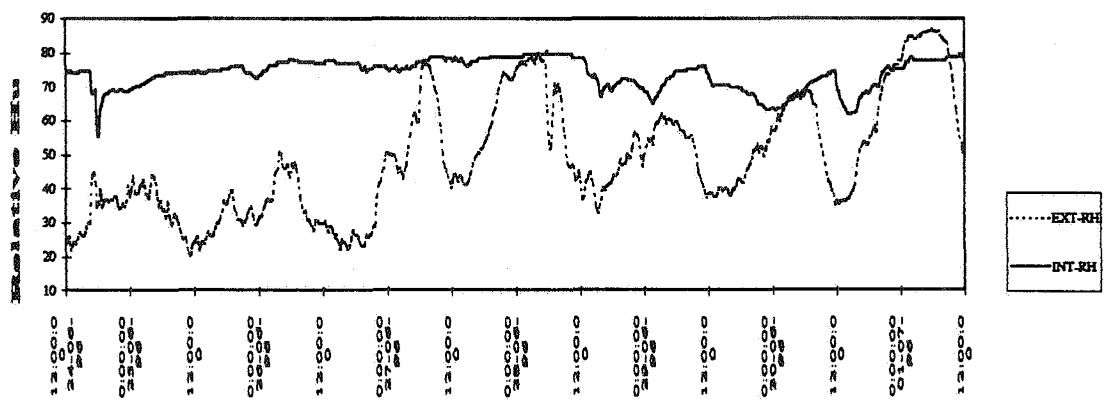


Chart 2: Building 3 - Relative Humidity

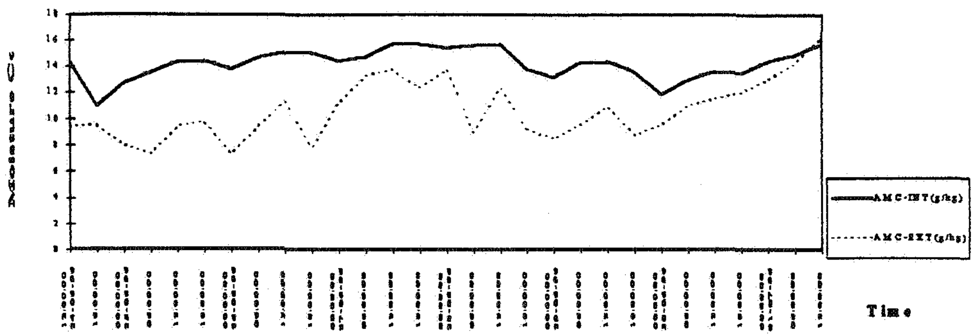


Chart 3: Absolute Moisture Content - Building 3

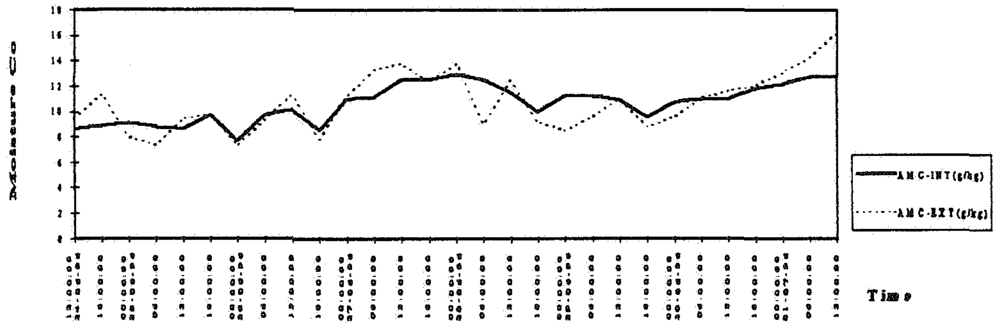


Chart 4: Absolute Moisture Content - Building 4

Initial consideration of the differences in the recorded temperature between the chimney and the external air would suggest that the chimneys operate on a diurnal cycle in the following way: the outside air temperature in the early afternoon is at its highest and is considerably higher than the inside, resulting in a downward air movement in the chimney. Direct gains from the sun and heat from the incoming air are absorbed by the walls and the roof of the house and from the chimney walls. The thermal mass gives back the heat at night, keeping the room temperature higher than the external which has decreased. Now the air flows in the chimney in the reverse direction, moving upwards. The temperature outside gradually increases as the day progresses and at some time the inside and outside temperatures become equal. At this instant, theoretically, there is no air flow in the chimney. In the early afternoon the outside temperature comes to its maximum again and the cycle repeats itself (See chart 5).

The monitored temperature data were used with the computer simulation software, BREEZE, [2] to model the natural ventilation of the buildings. These simulation results are given in Table 2, where column 3 gives the maximum daytime and the minimum night-time external temperatures, and column 7, the maximum and minimum temperatures inside the buildings and in the chimneys. The BREEZE-predicted total volumetric air-inflow and outflow rates for these temperatures are given in columns 8 and 10, respectively for the chimneys and the main spaces of the buildings. Also shown, where the flow through the chimney is non-zero, is the percentage contribution of the chimney to the overall air flow in the building. The final column expresses the volumetric air flow rates as air changes per hour for the whole building. It is reassuring to see that BREEZE predicts approximately equal air inflow and outflow for each building. Table 2 shows that the chimneys provide a significant contribution to the overall natural ventilation of the buildings. With the exception of Building 2, it can be seen that air flows down the chimney during the day, and up the chimney at night, as was expected. In Building 2, predicted air flow for the monitored temperature conditions is as was expected. In Building 2, predicted air flow for the monitored temperature conditions is always downwards. One possible explanation is that, because building 2 is deeply excavated, it stays cooler than the outside air at all times, thus creating a constant downward flow.

Chart 5 shows the performance of Building 4, in terms of air flow rate and direction through the chimney, and their change over time and with internal/external temperature difference. The external and room temperatures were those recorded over one day in the building during the monitored period, and the air flow rates are those predicted by BREEZE, using these temperatures. It can be seen how the direction of flow changes when the room temperature becomes greater or less than the external temperature. Table 2 shows that the buildings experience quite high ventilation rates. Although these fairly high ventilation rates maintain acceptable air quality in those rooms which experience the ventilation, humidity levels are generally unacceptably high in rooms isolated from the main air movement paths, and it is this aspect of these buildings which makes their rehabilitation most problematic.

The overall effectiveness of a chimney is determined by a number of factors, the most important of which are its location in the house and the height of the chimney. Chimneys located at the rear of an open-plan dwelling were shown to operate much more effectively than chimneys in small rooms or near large openings at the front, like the chimney in building 1 (fig. 1). Chimneys with a height greater than the surrounding buildings benefit from winds, when they are blowing, to create a wind-driven air flow, particularly useful when the temperature difference between the top and the bottom of the chimney is small.

It is difficult to improve a problematic chimney. Sometimes chimneys are in small, separate rooms, like the one in building 3. In this case, opening a large passage to the other rooms might improve the performacne of the chimney and its contribution to the overall ventilation. In the case of a chimney built lower than the surrounding buildings, the height of it should be increased. In vernacular buildings this is not always acceptable, because it alters the form of the house. However, it has been shown from this study that a well-designed chimney can be used as a means of improving natural ventilation, offering an alternative to cross ventilation, wherever the later is difficult to achieve.

		Ext.T. (°C)	Floor	Area m^2	Volume m^3	Temp. °C	INFLOW m^3/h	INFLOW %	OUTFLOW m^3/h	OUTFLOW %	A.C./h
Building 1	Day	42	Building	90.5	217.3	30.0	4268.7	83.3	5104.6		
			Chimney	0.1	0.1	37.0	855.3	16.7%	0.0		3.94
			Total	90.6	217.4		5124.0		5104.6		23.57
	Night	22.5	Building			24.0	1939.7		1515.2	78	
			Chimney			27.0	0.0		428.8	22%	1.96
			Total	90.6	217.4		1939.7		1944.0		8.92
Building 2	Day	42	Building	81.8	245.4	26.5	2204.0	29.8	7264.4		
			Chimney	0.3	1.1	28.0	5187.1	70.2%	0.0		21.05
			Total	82.1	246.5		7391.1		7264.4		29.99
	Night	22.5	Building			22.0	337.0	22.5	1496.6		
			Chimney			22.0	1159.6	77.5%	0.0		4.70
			Total	82.1	246.5		1496.6		1496.6		6.07
Building 3	Day	37.5	Building	102.2	306.5	26.0	8882.7	93.7	9470.2		
			Chimney	0.4	0.9	30.0	595.4	6.3%	0.0		1.94
			Total	102.6	307.4		9478.1		9470.2		30.84
	Night	22	Building			23.5	3539.6		3334.2	94.2	
			Chimney			22.5	0.0		204.7	5.8%	0.67
			Total	102.6	307.4		3539.6		3538.9		11.52
Building 4	Day	37.5	Building	40.5	117.7	28.0	6114.0	85.5	7124.0		
			Chimney	0.1	0.1	35.0	1033.5	14.5%	0.0		8.8
			Total	40.6	117.8		7147.5		7124.0		60.7
	Night	22	Building			26.5	5093.1		4579.3	90	
			Chimney			23.0	0.0		507.7	10%	4.32
			Total	40.6	117.8		5093.1		5087.1		43.25

Table 2: Results of Modelling Natural Ventilation

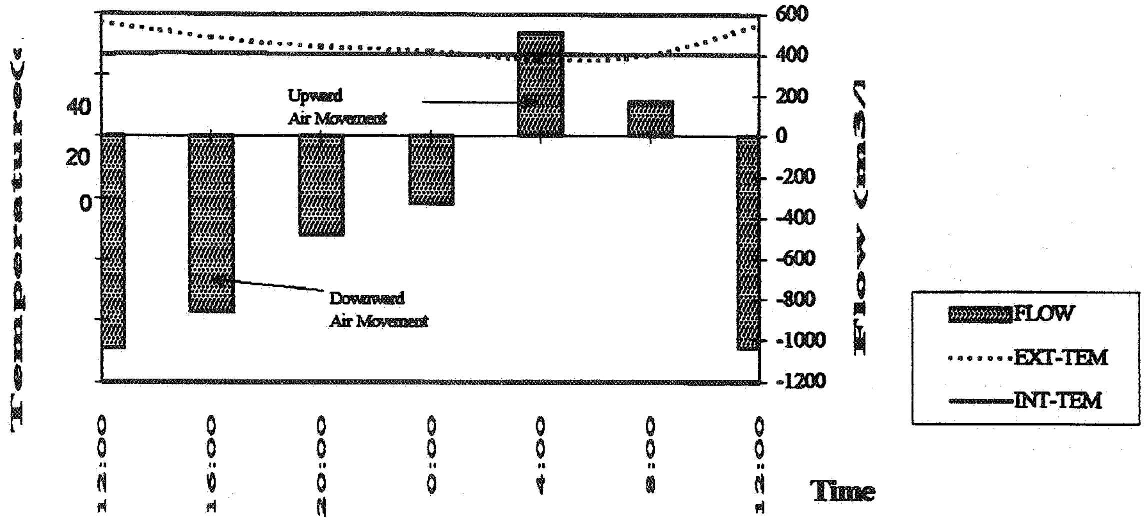


Chart 5: The Diurnal Ventilation Cycle for Building 4

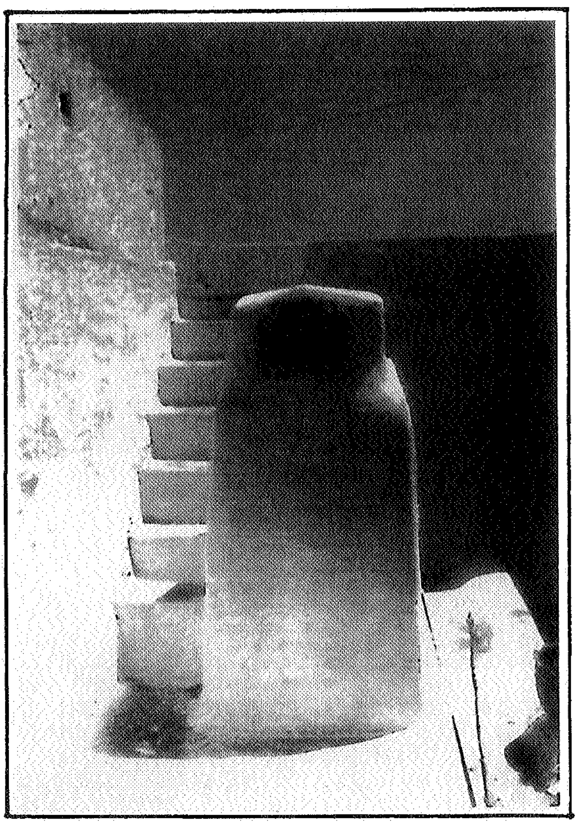
4. Summary and Conclusions

The results of this study were based on the monitoring of four selected buildings. In all cases it is obvious that the high thermal mass has a very important role, keeping the temperature stable and at a low level. However, the excavated buildings are deep in plan and cross ventilation is impossible, resulting in high relative humidities. It is here that chimneys prove to be very important. The more effective chimneys, like the one in building 4 increased the ventilation, giving a high ventilation rate and maintaining the humidity to outdoor values. The inappropriate location of some of the existing chimneys for beneficial natural through-ventilation calls into question whether the original vernacular builders fully understood the role of the chimneys. The preferred location seems to have been determined by the position of the cooking stove (often positioned near the entrance to the dwelling) rather than to promote good overall air quality and humidity control.

The experience gained from this study can be used in new buildings in Santorini or elsewhere. A chimney carefully designed and located at the right place has been shown to be able to provide ventilation to deep planned buildings or ones which cannot have openings on all sides. Nowadays the construction methods and materials are different to the traditional ones. In Santorini, excavated dwellings are no longer constructed, although existing excavated dwellings are restored and deserted ones are rehabilitated. Concrete and brick are the materials used to build new buildings. Contemporary architects, designing new buildings for the island and re-furbishing the old, should learn from the experience gained from studying these houses. Their designs should reinforce the benefits of the old-style vernacular buildings, such as high thermal mass, and should tackle the draw-backs, such as poor lighting and air quality. By employing well-designed chimneys to promote high rates of natural ventilation to control humidity levels, for example, architects may be able to respond to the contradictory needs of providing comfortable modern housing, without spoiling the fragile architectural quality of the island.

5. References

1. AWBI, H.B.
"Ventilation of Buildings"
E & FN Spon, London 1991
2. BUILDING RESEARCH ESTABLISHMENT, Department of the Environment,
"BREEZE 6.3: User Manual",
Crown, London 1995
3. EUROPEAN COMMISION, Directorate General for Energy (DG-XVII), Programme "SAVE"
"Passive Cooling in Hotels; Cycaldes"
CRES, Athens 1995,
4. FANGER, P.O.
"Thermal Comfort: Analysis and Applications in Environmental Engineering"
Mc Draw-Hill Book Company, New York 1972
5. GIVONI, B.
"Passive and Low Energy Cooling of Buildings"
Van Nostrand Reinhold, New York 1994
6. JONES, W.P.
"Air Conditioning Engineering", 3rd Edition, Chapter 2
Edward Arnold, London 1985
7. KOUMANOUDIS, I.N.
"Vernacular houses and churches of Santorini"
Danezis M., editor, Santorini, Athens 1971, p. 209-213 (in Greek)
8. MILNE, M. and GIVONI, B.
"Architectural Design Based on Climate"
in *Watson. D., editor, Energy Conservation Through Building Design,*
Mc Graw-Hill, New York 1979
9. STATUS INSTRUMENTS LTD
"Trend-Reader Reference Guide", Data Logger Analysis Software, Version 1.56 for DOS,
Status Instruments LTD, Canada



the chimney in Building 3