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Experimental approach to the thermal response of passive systems

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Abstract

The thermal performance of a passive solar heating system has been investigated via simultaneous temperature, velocity and flux measurements and their acquisition. The sensor locations inserted on the full scale model of a passive heating system, a single zone with a thermal wall, were on the walls and at the vents. The thermal wall of the zone is similar to the so-called Trombe wall in the literature, but it has no storage property. Experimental data showed that the wall black surface is sensitive to fluctuations in the solar intensity rate. Evaluation of the data using the definitions of the modified Rayleigh numbers concluded the existence of two extreme points. One of them represents the situation of the maximum amount of heat transfer to the room (test room). The second extreme situation is the beginning of the heat loss to the environment due to the reverse circulation process, namely night time cooling. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Thermal wall; Thermal response; Passive heating; Natural convection

1. Introduction

Environmental concerns accelerate the interest in passive solar heating, which is a phenomenon including natural actions, such as solar energy collection, its storage and distribution into the building structure. Although it is a very well known system and widely studied, management of the solar energy, its heat and fluid flow mechanism still needs optimization to achieve efficient use. The most detailed explanation and applications of these systems are present in the literature [1,2]. In Fig. 1, one of these applications, the Trombe wall system, is illustrated.

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Nomenclature

	surface area of thermal wall (m^2)
$_v$	cross-sectional area of ventilation holes (m^2)
	height of shaded region (m)
	gravitational acceleration (m/s^2)
	height of room (m)
	thermal conductivity of air (W/m K)
	Nusselt number
	channel width (m)
	temperature (°C)
$_I$	internal Rayleigh number
$_E$	external Rayleigh number
	average velocity at ventilation holes (m/s)
	rate of heat transferred to room (W)
	specific heat capacity of air (J/kg K)

Greek symbols

q	density of air (kg/m^3)
b	thermal expansion factor (1/K)
a	thermal diffusivity of air (m^2/s)
m	kinematic viscosity of air (m^2/s)

Subscripts

ch	channel
g	glazing
r	room
w	wall
upper	upper ventilation hole
lower	lower ventilation hole

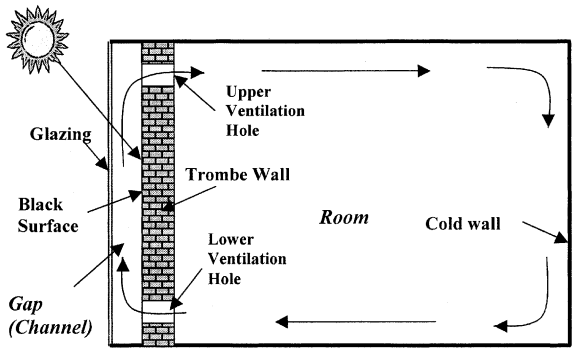

Fig. 1. Schematic diagram of a typical Trombe wall system and thermo-circulation process.

The historical development of experimental and numerical studies related to passive heating systems with thermal walls, originated from small scale analogies [3,4], has reached full scale investigations [5].

Warrington and Ameel [6], e.g., investigated natural convection heat transfer in a scaled test facility of a Trombe wall geometry. The experiments reported by Akbarzadeh et al. [7], including flow visualization in a full scale test facility, provided information on the effect of gap width and vent sizes on the thermo-circulation performance.

Similarity between the fluid flow in the gap and between parallel plates is another tool in the investigation of solar passive buildings. Akbari and Borgers [8], Fedorov and Viskanta [9] and La Pica et al. [10] theoretically solved the laminar natural convection between two parallel plates and obtained the velocity and temperature fields.

Most of the work appearing in the literature recently, uses the Rayleigh number based on the height of the enclosure as a tool. Warrington and Ameel [5] employed silicone oil as the heat transfer medium to obtain large Rayleigh numbers and found that the Nusselt numbers were higher on the Trombe wall gap side than on the living space side.

It is obvious that the heat transfer mechanism in the mentioned systems depends on the fluid flow in two sub-zones, namely, the gap between the glazing and the wall, and in the main zone, which is the space to be heated (Fig. 1). The fluid flow here is the movement of the air, and its characteristics are those of natural convection. That is why, in some of the investigations, the problem is titled natural convection in partitioned enclosures. However, the real problem of enclosures heated by solar energy by means of a thermal wall differs from the general aspects of air movement in enclosures due to two main aspects. First is the varying boundary conditions on the glazing. The solar intensity is not constant and periodical. The varying and undetermined conditions on the very left boundary, affects the variables on the other walls. The interior values of the temperature and velocity also depend on the solar intensity. The second challenge of the problem is its turbulent characteristics [11,12]. Thus, generalization of the problem needs for a lot of experimental data to be evaluated.

In the present study, the contribution to the possible correlation between the varying boundary conditions and temperature field has been examined. The experiments have been executed in a full scale Trombe wall system constructed at the Istanbul Technical University Campus located at latitude 41° N. Ventilation rates resulting from natural heating were also predicted [13]. Both the computational study and the experimental work, namely the obtained data to be analyzed to investigate the velocity field and the turbulent natural convection inside the room will be presented in a future paper.

2. Experimental apparatus and procedure

An external view of the facility is shown in Fig. 2. It mainly consists of two more spaces added to the test cell, namely the control room on the east side, where all the instrumentation is located, and the west room added to the facility to provide constructional and thermal symmetry. Thus, the east and west walls of the test cell behave as interior partitions. The test cell itself is a 3 3 3 3 3 m^3 room, and a glass cover in front of its south wall has been constructed. Unlike the Trombe wall reported in the literature [5], the south wall has a very slight thermal storage

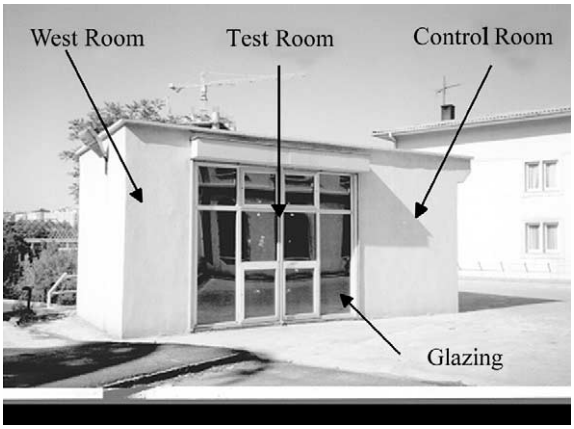

Fig. 2. Test facility.

capacity. For convenience, this wall will be called the thermal wall. The 0.16 m thick south wall was made of brick and the mat black painted outer surface was measured to be 3 3 3 m^2. Four pairs of rectangular vents, each 0 5 m 0 2 m, were located at the bottom and top of the wall, 15 cm from the floor and ceiling, respectively. The glass double glazing cover was located 0.2 m in front of the south wall.

The aspect ratio of the room, defined as the ratio of the height to the length ( ), is 0.9. The east wall, west wall, ceiling and floor were insulated by using 30 mm thick styrofoam panels in order to reduce the uncontrolled heat losses and provide two dimensionality in the cross-sectional plane.

Since the thermal response of the south wall has an important effect on the performance of the whole system, the primary experiments were focused on determination of the temperature distribution on the black surface. The temperature measurements within the room and at the vents and also the velocity rates at the vents were taken for assessment of the thermo-circulation characteristics and the thermal performance. During the temperature and velocity measurements, solar radiation was also recorded by using a KIPP-ZONEN CM-21 Pyranometer. Temperature measurements were taken with previously calibrated K-Type, Teflon coated thermo-couples of 0.0004 m diameters on the wall and 0.0002 m diameters in the space. The thermo-couples used to collect temperature data on the black surface and the glazing were fixed on the surface by aluminum tape to prevent exposure to direct sunshine. Thermo-couple probes were connected with extension wires to a data acquisition (DAS) board terminal, which is capable of reading as low voltages as generated by the thermo-couples. Then the data, converted to digital units, were stored on the permanent disk of a PC, located in the control room. As for the velocity measurements at the vents, a DANTEC Low Velocity Analyzer-54N50 was employed, which consists of a hot film based omni-directional velocity probe and an electronic main unit. The analyzer incorporated a temperature sensor to compensate the effects of temperature fluctuations in the air stream. Similar to the temperature data, the velocity and solar data were also stored on the PC through the DAS. A metallic case mounted above the thermal wall contains a rolling shutter, enclosed to shade the thermal wall (Fig. 2). It is observed that the shaded area varies very little throughout the day.

3. Experimental results and discussion

3.1. Thermal response of the surfaces

First of all, the thermal response of the wall has been investigated by taking temperature measurements on the black surface. Thermo-couples were placed on the surface as shown in Fig. 3 so that the response of the whole wall may be deduced. On Fig. 3, the numbers from 1 to 7, both in the vertical and horizontal directions, represent the temperature measurement locations. Starting at the top, a 1.2 m portion of the wall is shaded and the temperature measuring points 6 and 7 in the vertical direction are within this area. All the other measuring points, aligned in the horizontal direction, were exposed to direct sunlight.

Since solar radiation is the unique source of the energy collected and distributed within the system, data from the measurement of solar intensity is important for interpreting the temperature distribution and the changes throughout the experimentation period. Therefore, the data collected in a minute-by-minute basis with the pyranometer has been plotted as shown in Fig. 4. The reason for the fluctuations observed in Fig. 4 is the partly cloudy weather characteristics of the plotted part of the measurement period.

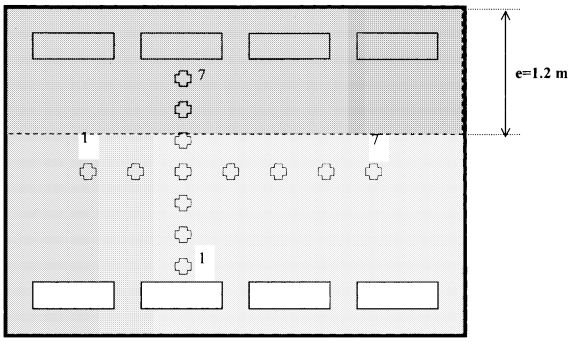

Fig. 3. Thermal wall front view.

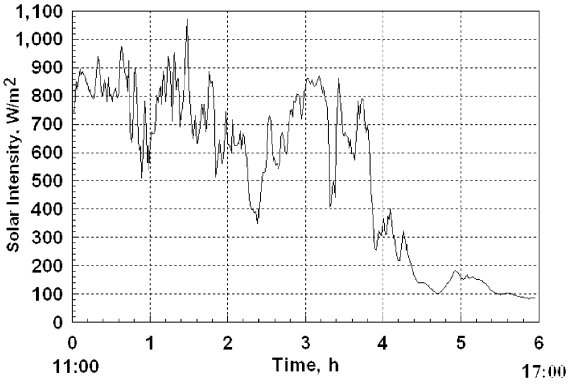

Fig. 4. Solar intenisty rate throughout a part of the experimentation period.

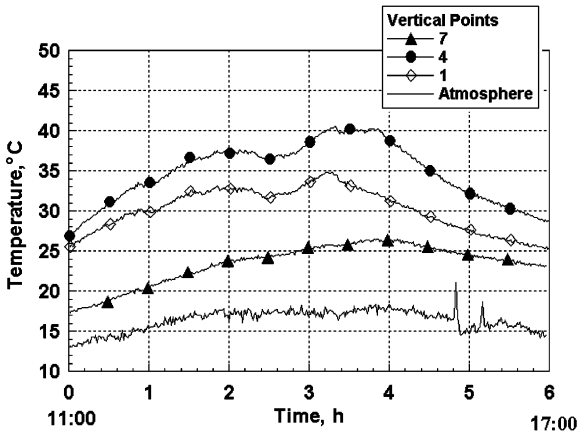

Fig. 5. Temperature variation in the points aligned in vertical direction on thermal wall black surface.

The temperature measurements taken on three typical points along the vertical line are plotted in Fig. 5. Points 1 and 4 could be assumed to have equal temperature values initially. However, the point above, point 4, has always a higher temperature than the point just above the lower vent. The observed temperature difference is due to the change in the trajectory of the sun. The point 1, being located just above the lower ventilation hole, meets the cooler air drawn from the room, as soon as it enters the gap region. The temperature fluctuations between the hours 2 and 4 are seemed to be consistent with the solar intensity plot also illustrated in Fig. 4. Unlike points 1 and 4, the temperature at point 7, which is within the shaded region, did not increase so much and created a smoother temperature profile. This profile is supposed to be caused by diffuse solar radiation and the heat transferred from the bottom region by convection. On the other side, the ambient temperature was observed to be well below the black surface temperature throughout the experiment.

For the points aligned in the horizontal direction, the temperature variations for the three points 1, 3 and 7 with respect to time are similar and equivalent to that of the point number 4 in the vertical alignment (Fig. 6). Very little differences can be observed in the first and in the last hour of the experimental period. This is also related to the solar trajectory from east to west. None of the points is continuously shaded by the vertical frame supports.

A further step for investigating the performance of the system was to consider the thermal response of the thermal wall black surface together with those of the glazing and the cold wall. For the sake of convenience, a part of the measurement period representing a clear, bright day with high solar intensity rates was investigated. As may be seen on Fig. 7, for this part of the data, a steady atmospheric temperature around 23 °C was recorded. At the beginning of the experiment, the temperature on the glazing was higher than that on the black surface, but the increasing temperature of the black surface equaled that of the glazing within 1.5 h (Fig. 8). Then, it went higher than the glazing temperature, making the system similar to a solar collector. In the middle of the experimentation period, a 5–8 °C temperature difference was reached and maintained until the end of the period. Unlike the black surface and the glazing, the change in temperature of the cold wall surface was very smooth and small. Although the cold wall has never received solar

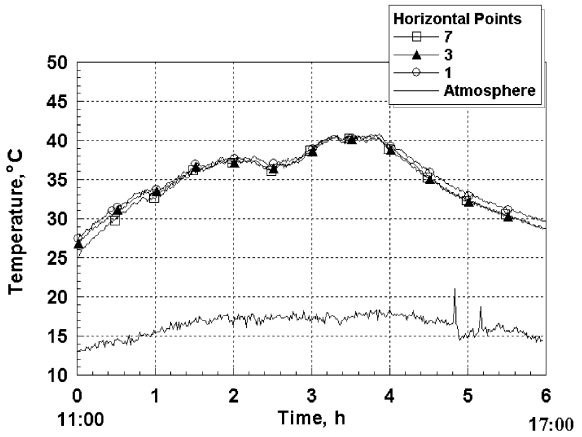

Fig. 6. Temperature variation in the points aligned in horizontal direction on the south facing thermal wall black surface.

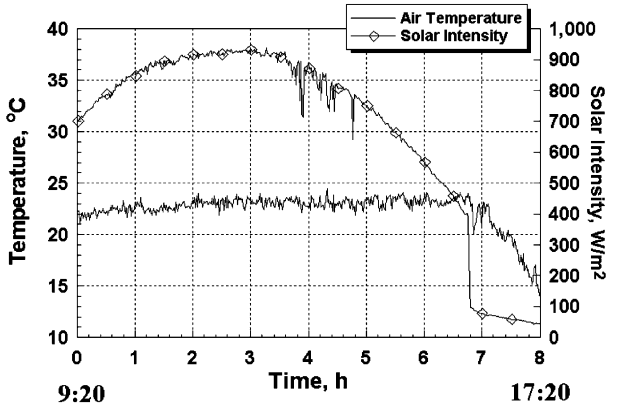

Fig. 7. Solar intensity and outside air temperature variations with respect to time.

radiation, the rise in its surface temperature indicates the occurrence of the thermo-circulation process inside the heated section.

The thermo-circulation process is expected to warm the air in the gap and cool it by the cold wall surface. Thus the cold wall surface is warmed, and consequently, its temperature rises. Initially, having a lower temperature than the ambient seems to create a conflict for the cold wall. The overnight cooling of the system and the thermal inertia of the wall might be the probable reason for the situation.

Another part of the data was for a mostly cloudy day (Fig. 9). The effect of cloudiness could be apparently observed as temperature fluctuations in the thermal wall black surface and glazing temperature values (Fig. 10). However, the surface temperature measurements seemed to follow a similar trend with those of the previous test. Within the first 2 h, the glazing had a higher temperature than that of the black surface, but later, the temperature measurements taken on the black surface were higher. However, they have intersected several times. Also, the cold wall temperature

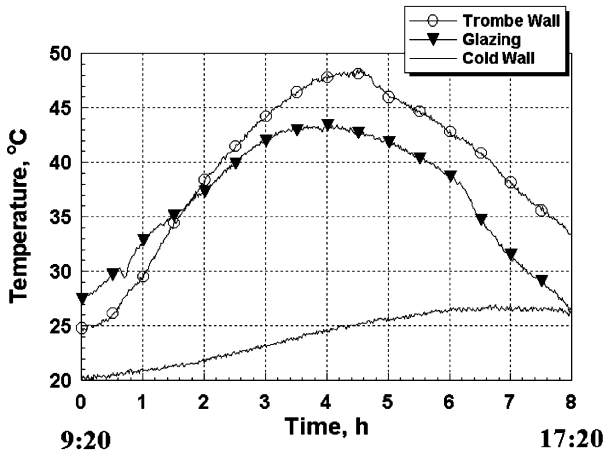

Fig. 8. Temperature variation on thermal wall black sruface, glazing and cold wall surface through the experimental period.

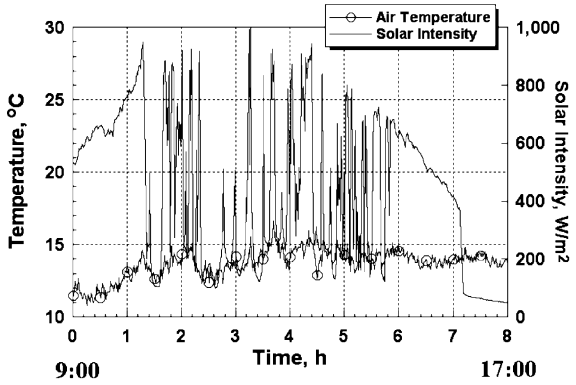

Fig. 9. Solar intensity and outside air temperature variations with respect to time.

profile behaved very similar to that of the previous set of test results. It increased slightly, but not significantly, throughout the period. The cold wall temperature was not affected by the high fluctuations of the solar intensity rate.

A more comprehensive part of the test data monitors the system continuously for a period of 24 h, namely, the temperature values on the thermal wall black surface, glazing, cold wall, thermal wall inner surface and the solar intensity rate (Fig. 11). The system escaped from direct solar radiation at around 17:00 and was re-exposed at around 7:00 next day. The temperature of the glazing seemed to be above that of the thermal wall black surface with a difference of 5 °C till the afternoon, and then it cooled to below the black surface temperature and maintained a 2–3 °C difference until the end of the test period. The temperature difference and the time duration are strongly dependent on the solar intensity rate and the outside air temperature. The thermal wall inner surface temperature was slightly higher than the cold wall temperature, resulting in a Rayleigh number (bD ^{3} m^{2}) in the range of 10^{10} in the room throughout the experimental

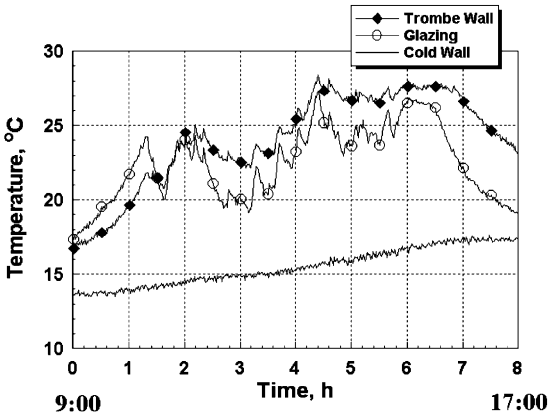

Fig. 10. Temperature variation on thermal wall black surface, glazing and cold wall surface through the experimental period.

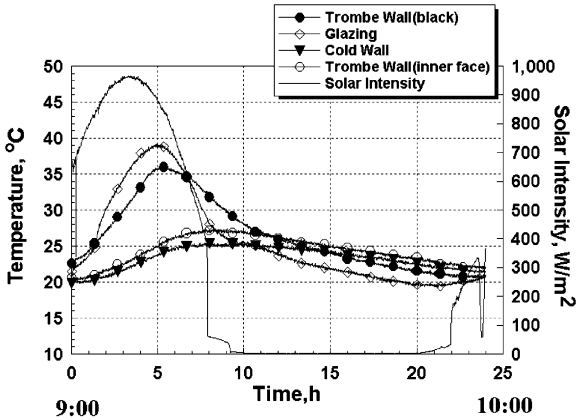

Fig. 11. Temperature variation of the thermal wall, glazing and cold wall throughout a day.

period. From the fluid movement point of view, a transition to turbulence is expected inside the heated zone [11]. Another expectation concerns the heat transfer mechanism inside the south wall. The temperature difference between the black and the inner surfaces disappears for the period without sunshine.

Besides the surface temperature values, space temperature values at specific locations: living space, outside, upper and lower vents, have also been recorded for use in assessment of the performance (Fig. 12). It may be seen from Fig. 12 that the temperature at the upper vent was the highest and the temperature at the lower vent was the lowest, while the temperature of the living space had a value in between throughout the experimentation period. This result is consistent with the thermo-circulation process. The outside air temperature was seen to have a big change from day time to night time.

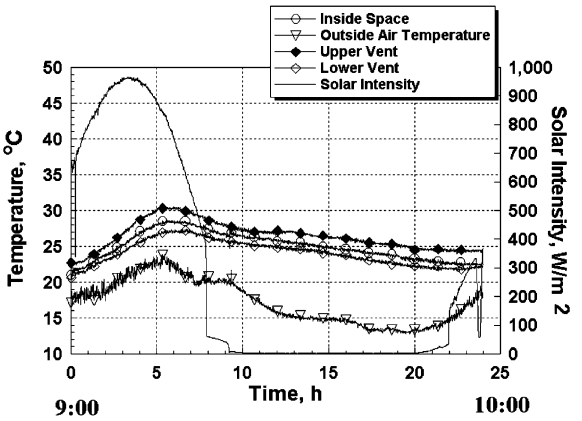

Fig. 12. Temperature variation of the heated zone, outside air, upper and the lower ventilation holes throughout a day.

3.2. Heat transfer characteristics

Comparing Figs. 11 and 12, it is concluded that the inside air temperature and the inner surface temperature of the thermal wall has almost the same profile. This trend means that heat is carried from the gap into the room by means of convection through the ventilation holes, and the conduction heat transfer through the wall can be neglected. Thus, the heat transfer analysis should be focused on the convection based terms. In the present study, internal and external Rayleigh numbers, introduced by Ormiston et al. [14] are used as tools of the analysis. The internal Rayleigh number, $_I$,

$$_I \quad \frac{b \quad _w \quad _g \quad ^3}{ma} \tag{1}$$

and the external Rayleigh number, $_E$,

$$_E \quad \frac{b \quad _{w\ g\ 2} \quad r \quad ^4}{ma} \tag{2}$$

represent the natural convection inside the channel and through the room, respectively.

The heat transferred to the room through the ventilation holes is calculated as the following:

$$q \quad _{v\ p} \quad _{upper} \quad _{lower} \tag{3}$$

Since the conduction heat transfer to the room from through wall is neglected, the net heat may be assumed to be transferred by convection, which has been defined above (Eq. (3)). Thus, should a Nusselt number be defined, the method below may be followed:

$$_ \quad \frac{D}{} \quad \frac{}{_w \quad _g \quad 2 \quad _{ch}} \tag{4}$$

The heat transferred into the channel via both of the surfaces, the glazing and the black surface of the wall is

$$1 \quad 2 \tag{5}$$

where

$$\frac{1}{2} \quad \frac{g}{w} \quad \frac{ch}{ch}$$

Assuming the heat transfer coefficients in the vi
heat transfer surface areas equal, it is obvious t
the heat ca d into the room through the
Nusselt num r based on the channel width:

$$\frac{\dot{Q}}{w \quad g} \quad \frac{upper \quad lower}{2 \quad ch} \quad \frac{upper}{a \quad w \quad g}$$

The last tion concludes the criteria for
ature at th er ventilation hole is always g
velocity in he channel should be downw
Nusselt nu s the one where the average c
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The in leigh number, on the other
coincidi case where the glazing tem
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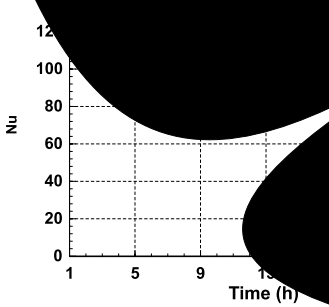
$$\frac{upper}{\frac{E}{I}}$$