

TROPICAL MODELING OF CONCRETE-CORE-RADIANT COOLING SYSTEM “Application On Alexandria, EGYPT“

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ABSTRACT

Present investigation is concerned to both experimental and numerical performance modelings for Thermo-Active-Building-Systems “TABS” especially Core-Cooled-Concrete-Slab, cooling system used in exposed roofs at moderate climatic region in Egypt such as Alexandria that have ambient temperature around 30.0°C at relative humidity reaching 90%, with solar intensities less than 550 W/m². Investigations were achieved by using custom made test-facility that able to test standard size of samples having 0.75m Length, 0.75m Width, 0.12m Thickness. These samples are representing part of real roof. The test facilities is equipped with lighting facilities, humidification and heating sources to simulate outdoor conditions with solar radiation, and Variable speed fans to simulate wind configurations from one side of slab “exposed” and have a constant indoor temperature controlled chamber to simulate room conditions at the inner slab surface “other side”.

With the aid of this custom made test facility, external slabs surface, slab core temperatures, embedded pipe temperatures and heat flux intensities were experimentally measured during simulated climatic condition periods at Alexandria governorate, the second Capital of Egypt. Climatic conditions were simulated based on averaged weekly temperature distributions recorded over a year leading to real year simulation within 52-Days “The duration of one experiment”. Measurements are conducted with the aid of state-of-the-art probes and sensing elements that wired to data acquisition and controlling unit which are managed via pre-programmed computer handmade software. Almost two months were required to execute one experiment. Each experiment provides valuable and huge collected data. These gained data allow for better understanding of the actual behaviours of TAB system and the expectations of thermal impacts on buildings. Results show that Cooled Concrete Radiant Slab, CCRS can not work alone for exposed roofs without efficient thermal insulation. Although, TAB system shows an effective cooling capacity from 34.0W/m² to

50.0W/m² but it can shave the peak loads and reduce the initial and running costs of the applied cooling systems by maintaining stable Energy Efficiency Ratio, “EER” at the optimum conventional cooling system performance.

INTRODUCTION

Thermo-Active-Building-Systems “TABS” is one of the radiant systems that utilize hydraulic circuits of pipes embedded in building structures, depending on pipe position. These TABS can be used in, floor, wall, ceiling and roof as radiant systems. The most recent application of radiant systems is the active thermal slab [1]. This type of systems belongs to ceiling/roof radiant types, but its constructive and operating conditions are different from other mentioned types: the pipes are embedded in the concrete structure, in order to get more mass and thermal capacity. Due to the construction technique, these systems are particularly suitable for multi-story buildings [2]. The Design of active thermal slab is based on the characteristics of other radiant systems (i.e. distance, length per square meter and diameter of pipes, thickness of the concrete layer, position of pipes inside the concrete, supply water temperature, water mass flow rate) [3]. Commonly the pipes are positioned in the centre of the concrete slab, with diameter ranged from 0.012m to 0.02m and a distance ranged from 0.10 m to 0.20m [4]. Two important aspects concerning this system are, firstly, related to cooling/heating period, is the risk of cold down draft at windows, which may be solved by the design of windows with U-factor less than 1.20 W/m².°K, or with extra cooling in the perimeter area [5]. Secondly, referred to the cooling period, is the control of humidity which may limit the cooling capacity of the system, as surface temperatures needs to be above the dew-point of adjacent environment to avoid condensation [6].

Peak-shaving could be possible by working during the night to cool the slab, which release the day after the energy stored during the night. In ISO-standards [7] and guidelines [8] on

environmental reference to steady state conditions is made; this hypothesis is still valid for rates of change in operative temperature of less than $\pm 5.0^{\circ}\text{C}$ per hour [8]. In the standards ISO-EN-7730 and ANSI/ASHRAE-55 the comfort range is $20.0^{\circ}\text{C} - 24.0^{\circ}\text{C}$ in winter and $23.0^{\circ}\text{C} - 26.0^{\circ}\text{C}$ in summer [7]. The operating conditions may therefore vary slightly during the day, but still remaining into the comfort range.

NOMENCLATURE

TAB(S)	N.A.	Thermal-Activated-Building System
CCRS	N.A.	Core-Concrete-Radiant-Slab
EER	kW_c/kW	Energy Efficiency Ration
3D	N.A.	Three Dimensional Curve
Gen-Set	N.A.	Chilled Water Generation Set
Dia.	[m]	Diameter
T_{So}	[$^{\circ}\text{C}$]	Outside Surface Temperature
T_{Si}	[$^{\circ}\text{C}$]	Inside Surface Temperature
T_{CL}	[$^{\circ}\text{C}$]	Conductive Surface Temperature
W_t	[$^{\circ}\text{C}$]	Average Chilled Water Temperatures
R_t	[$^{\circ}\text{C}$]	Average Lower Chamber Temperatures
Rm.	N.A.	Room
N.A.	N.A.	Not Applicable

METHODOLOGY

Physical modeling was carried out with the aid of experimental measurements in a test facility and was assessed with numerical modelings. Available test facility enables us to estimate the cooling capacity of the CCRS. In the previously conducted work, [3] which was based on theoretical calculations and numerical simulations as well as measured indicators, TABs is found to be a useful as an assistant system for conventional cooling system, and that at the same time, it can also be used for heating as presented by previous investigators, [1], [2], [5].

The methodology of the applied experimental measurements is to consolidate the thermal characteristics of CCRS as an assistant part of the commonly used cooling systems in Alexandria where climatic conditions are Warm and Humid. These experiments were accomplished by exposing a part of real slab to artificial climatic conditions similar to a pre-selected climatic region for certain periods. These artificial climatic conditions have to simulate the averaged weekly temperature, solar radiation, humidity, and wind speed distributions recorded over a year. Climatic conditions were collected from W-Underground.com and Energy-Plus.com websites, [9], [10]. These data were compared and adapted with the averaged ten years data collected from the Egyptian Authority for Climatic and Aviation, [11]. Using automated controllers and data acquisitions of the test facility, the weekly climatic conditions were established and converted to group of hourly “time-dependent” orders and actions for different components of the test facility for a period of 52-days.

Figures 1, 2, 3 and 4 show the three dimensional, 3D averaged weekly Temperatures, Relative Humidities, direct solar radiations, and Wind Speeds distributions respectively

recorded over a year using 3D grids, Parameters are listed Along Z-Axis with weeks of a year along X-Axis and hours of day along Y-Axis.

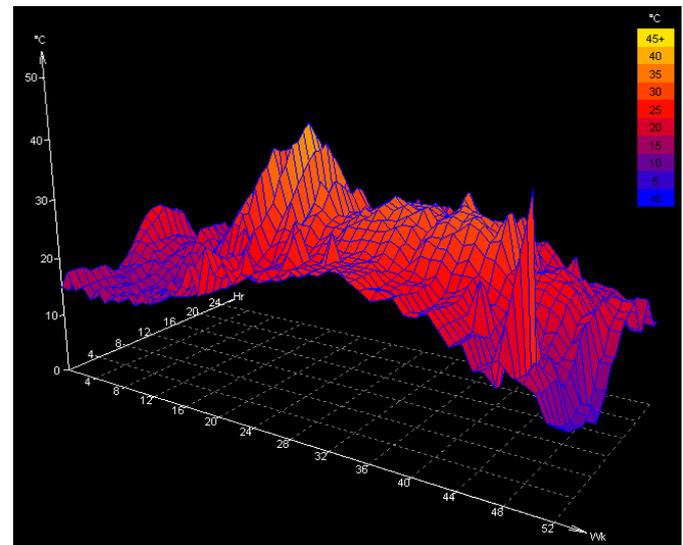


Figure 1 3D Averaged Weekly Temperature Distribution Recorded Over A Year Using 3D grids, Temperature [$^{\circ}\text{C}$] Along Z-Axis With Weeks of Year Along X-Axis & Hours of A Day “24-Hours” along Y-Axis.

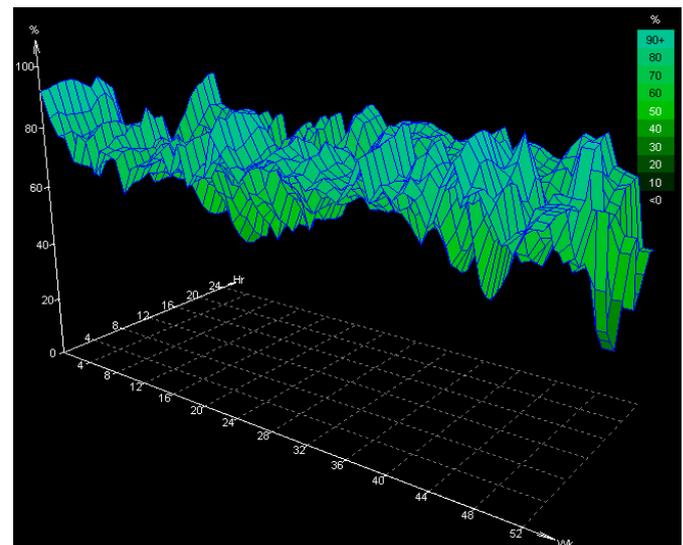


Figure 2 3D Averaged Weekly Relative Humidity Distribution Recorded Over A Year Using 3D grids, RH [%] Along Z-Axis With Weeks of Year Along X-Axis & 24-Hours along Y-Axis.

Exposed slab surfaces, slab core temperatures, embedded pipe temperatures and heat flux intensities were measured during the simulated climatic condition periods “The duration of one experiment”. Measurements are conducted with the aid of state-of-the-art probes and sensing elements that wired to data acquisition via multiplexers and control unit which are managed from pre-programmed computer custom made software.

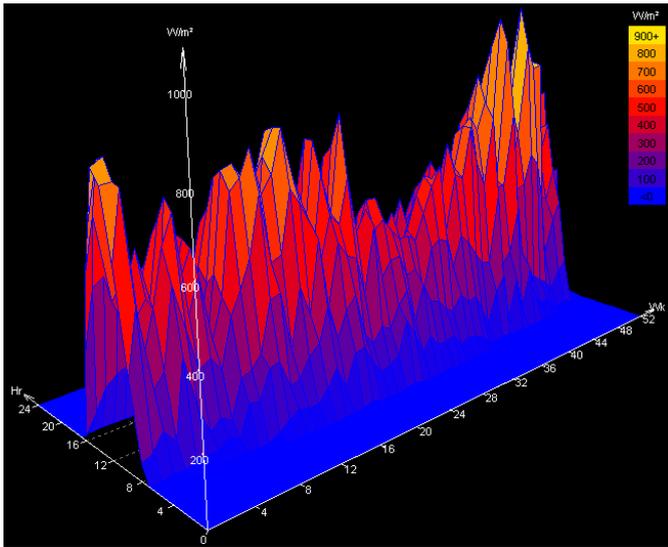


Figure 3 3D Averaged Weekly Direct Solar Radiation Distribution Recorded Over A Year Using 3D grids, Solar Radiation [W/m²] Along Z-Axis With Weeks of A Year Along X-Axis & Hours of day along Y-Axis.

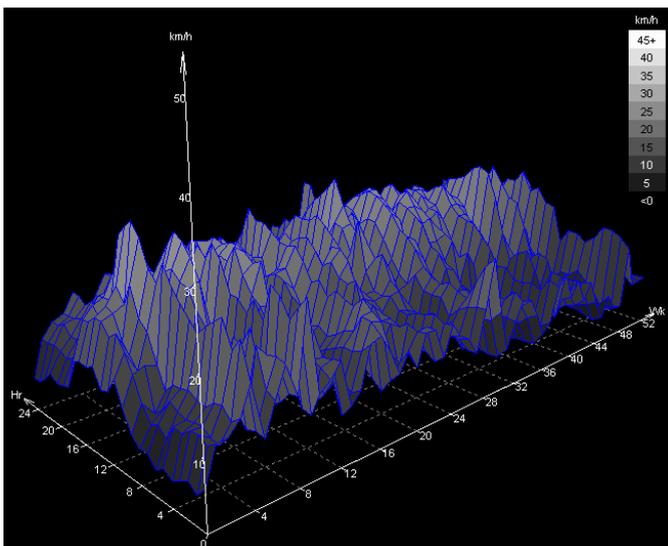


Figure 4 3D Averaged Weekly Wind Speeds Distribution Recorded Over A Year Using 3D grids, Wind Speed [km/h] Along Z-Axis With Weeks of A Year Along X-Axis & Hours of day along Y-Axis.

TEST FACILITIES SETUP

The test facility is a room of 4.35 m times 3.80 m with a height of 3.75 m which, is air-conditioned by 7.0 kW_C cooling capacity unitary unit. Inside this controlled atmosphere room the test rig was placed. Test-rig was constructed based on two thermally treated and controlled chambers. These chambers are separated by the concrete sampled slab. The lower chamber simulates control volume of the indoor conditions and it is well thermally isolated and has a separate heating or / with cooling 3.5 kW_C air-conditioner that enables part loads from 10% to

100% during heating and from 80% to 100% during cooling, while the upper chamber shall simulate the outdoor conditions.

Figure 5 shows the schematic layout of test-rig, where a variable speed (VSD) fan will blow air through a transformed duct, that equipped with multi-bank electrical heaters and air straightness, to the void of upper chamber. This moving air will flow over the upper surface of the sampled slab to simulate wind at certain temperature. In addition, the combinations of VSD fan flow variation with the electrical heater power variations could simulate any real wind or gust speeds at specified outdoor air temperatures. The lower surface of slab will be exposed to controlled temperature chamber that simulate the indoor space temperature. This chamber could be controlled in-dependently according a pre programmed operation profile.

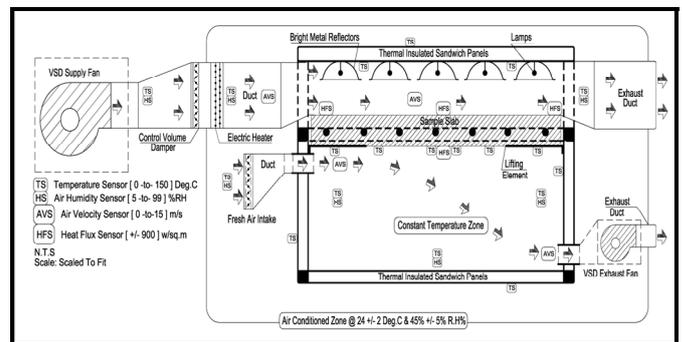


Figure 5 Schematic Layout of Test Rig Setup



Figure 6 Isometric View of Test Rig Facility Layout

Figure 6, 7, 8 and 9 show isometric and front views pictures for the main test-rig components.

Temperature distributions of slab surfaces and embedded pipes have been obtained with the aid of solid state sensors NEC-LM35 at +/-0.08 °C accuracy, the distribution of the local mean temperatures for air and slab surface have been obtained with the aid of thermal positive coefficient-thermistor sensor KG400n and resistant-temperature-device (RTD), at +/-0.10 °C accuracy, the heat flux was obtained by using heat flux

sensors [Heatex-EXDR234], (0.0-1000.0 W/m² +/-5% @ Full Range) and temperature transducers. Data were collected and control actions were executed by using data acquisition system DAQ-12 [LabJack R456 12Bit] including the multiplexers, dimming cards and controlled relays card which are assembled inside a handy bag to be portable and this assembly is connected to a PC computer operated with Lab-View Ver.7.0.0.software, [11].



Figure 7 Schematic Layout of Test Rig Setup



Figure 8 Three external boundary condition types

A self-contained 0.04 m³ storage chilled / hot water generator, Gen-Set is connected with TAB sample slab “located inside test rig” via quick couplings to provide TABs with the desired water flow rates at specific fixed temperatures.



Figure 9 Test-Rig Supply Fan Section and Lighting Fixtures Over Slab For Simulating Wind Speed & Solar Radiation

This Gen-Set able to produce chilled water at pressure up to 3-bars and at temperature ranger from +4.50°C up to +70.0°C with tolerance +/-1.50°C. Experiments on different constructions, embedded pipe grid arrangements were carried out for performance predicting of CCRS at desired climatic conditions.

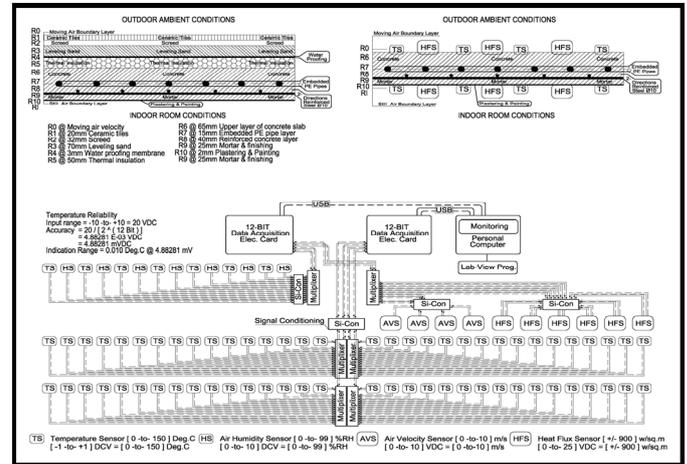


Figure 10 Schematic and Wiring Diagrams for 72-Channel Data Acquisition and Control Modules

EXPERIMENTAL SETUP

Figure 11 shows schematic layouts and dimensions for some sampled slabs with the piping arrangements and the footprint dimensions including spacing among pipes, inlet and outlet connections and the anticipated locations for the temperatures, heat flux sensors, all used slabs have the same overall dimensions of 0.72 m Length, 0.72 m Width and 0.120m except that the over all thickness may changes according to the number of build-up layers over base case slab.

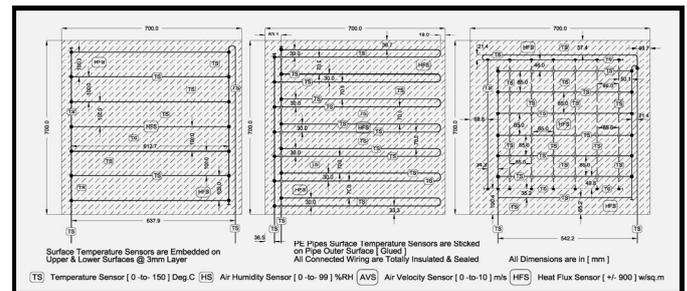


Figure 11 Schematic and Wiring Diagrams for 72-Channel Data Acquisition and Control Modules

Figure 12 shows layouts of the wooden frames “dies” that were used to cast all concrete blocks and inside it the reinforcement Dia-0.01 m steel bars at spacing of 0.15 m, the latter is always located at lower level of the concrete slab at 0.02 - 0.03 m from the slab bottom surface. The figure is also show four types “B, C, D, E & F” of Dia-0.015 m piping arrangements and type. The Dimensions for all sampled slabs are 0.72 m times 0.72 m which is equal 0.50 m² with 0.120 m and up to 0.150 m thickness. The slab Type-A was constructed

as a standard base case without any CCRS piping. It was well known thermal behaviours and was documented. This slab was used as a tool for calibration in order to consolidate the proper operation of test rig.

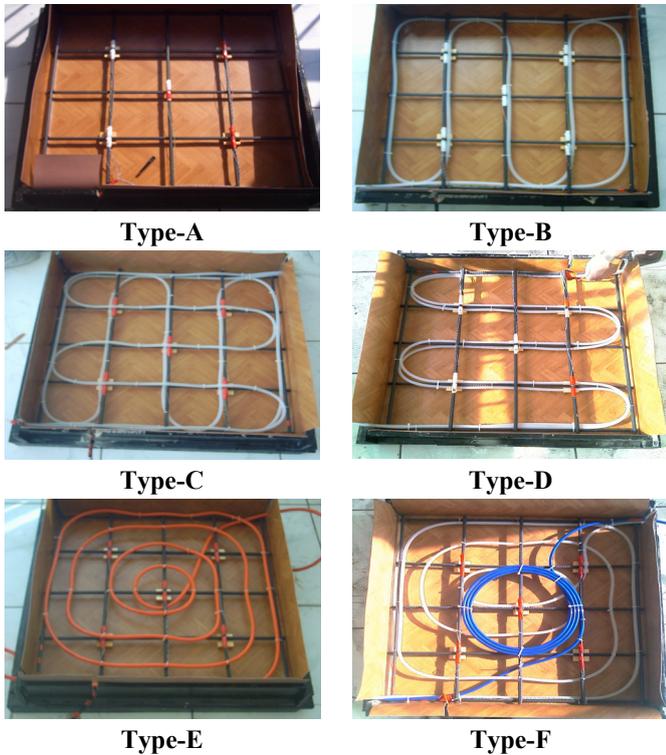


Figure 12 Pictures of The Base Case And The CCRS Piping Arrangements Inside Wooden Dies Before Concrete Casting

NUMERICAL METHOD

Design assessment utilizes numerical modelings software for establishing adequate methods for evaluating different cases to minimize research cost and time. Software was adopted to solve the continuity, three momentum, energy governing equations and water vapour transport equations. The details of the governing equations and the solution algorithm can be found in references [12, 13, and 14]. Numerical method used two turbulence equation models by Launder and Spalding, [12]. The solution of the governing equations can be realized through the specifications of appropriate boundary conditions. The values of velocity, temperature, kinetic energy, and its dissipation rate were specified at all boundaries. External Walls: A non-slip condition at all solid walls is applied to the velocities. The logarithmic law or wall function has been used as Launder and Spalding [13], for the near wall boundary layer. At inlets the air velocity was assumed to be of a uniform distribution; inlet values of the temperature were assumed constant value and uniform distribution. The kinetic energy and its dissipation are estimated as to allow for nearly 5% turbulence intensity at air inlet. The initial values of the dissipation rates were computed from known values of initial kinetic energy of turbulence and dissipation length scale at air inlet.

RESULTS AND DISCUSSIONS

Experimental Results

Figure 13 shows the experimental measurements of the base case Type-A, which represents the simple reinforced concrete slab. temperature distributions are for upper slab surface T_{SO} without solar radiation effect and lower surface temperatures T_{SI} . the figure illustrate the peak differences between exposed and indoor surfaces of slab at about 12.0 °C with time lag approx. 120 minutes, these results have same trends as reality.

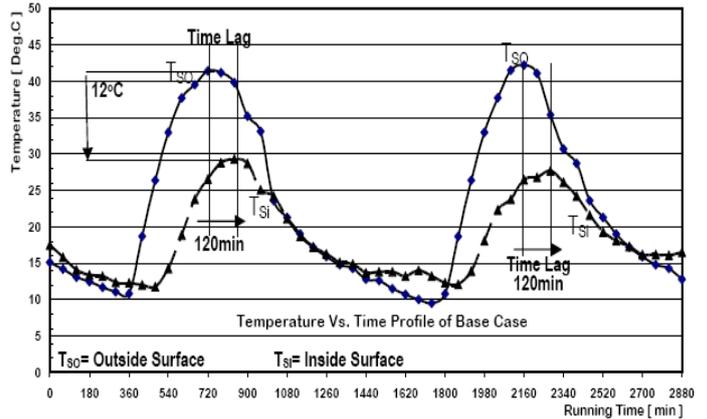


Figure 13 Experimental Results of Base Case Concrete Slab

On the other hand Figure 14 illustrates main characteristic curves for the Type-D exposed slab surface T_{SO} , indoor slab surface T_{SI} , average steel bars temperature (virtual conductive layer) T_{CL} at, and outlet chilled water temperatures T_{WO} . It was notice that during tests the difference between inlet and outlet chilled water temperatures is fluctuated between 2.5°C and 3.2°C. The peaks differences between exposed and indoor surfaces of tabed slab were about 16.0°C with time lag about 440 minutes, in addition to the sensible peak shaving and curve smoothness.

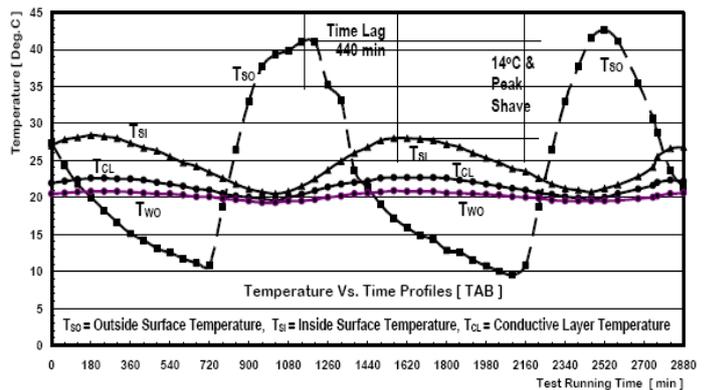


Figure 14 Experimental Results of CCRS Concrete Slab

Gained results gave well understanding for the applicability of CCRS as a cooling systems especially for the transferred and absorbed heat fluxes through CCRS as listed in next table:

W_t / R_t	12.55 m/m ²	10.43 m/m ²	8.4 m/m ²
15.0°C	88.3 W/m ²	73.7 W/m ²	70.3 W/m ²
at 30.0°C	at 23.0°C	at 21.8°C	at 20.0°C
19.0°C	70.2 W/m ²	58.7 W/m ²	50.2 W/m ²
at 31.0°C	at 24.5°C	at 23.5°C	at 21.5°C
23.0°C	34.7 W/m ²	34.7 W/m ²	32.6 W/m ²
at 32.0°C	at 26.8°C	at 25.8°C	at 25.0°C
26.0°C	29.5 W/m ²	25.5 W/m ²	22.5 W/m ²
at 33.5°C	at 28.9°C	at 27.4°C	at 28.9°C

Where;

(W_t) is the average chilled water temperatures and (R_t) is the anticipated average lower chamber temperatures. Listed heat fluxes W/m² are rated to lower slab surface temperatures.

Cooling capacity rating graph indicated on Figure 10 is plotted for eight different measured averaged room temperatures. This graph describes the relation between chilled water mean temperatures flowing inside CCDS and the anticipated cooling energy that could be reached based on pipe arrangements Type-C at 0.15 m piping spacing, 0.15 m pipe diameter and pipe length 15 m/m² “pipe length per square meters of slab area”. In other words this shows the cooling capacity of the ceiling surface. In all cases the cooling is less than 2°C, giving uniform surface temperatures. On the graph, each point represents one measurement series. Also notice that there is a near linear correlation between the chilled water mean temperature and the heat flow through the slab surface.

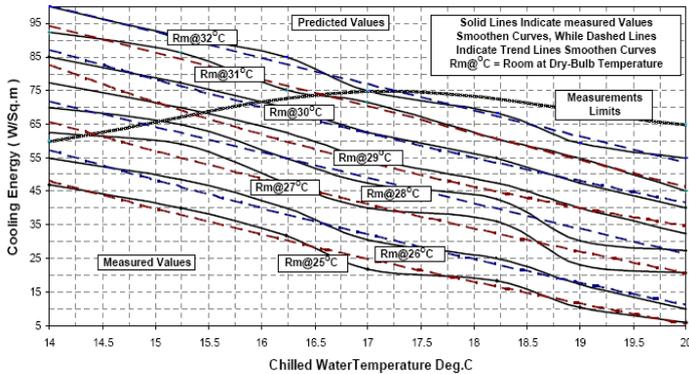


Figure 15 Measured & Predicted Cooling Energy “Capacity” for TABs Type-C Vs. The Mean Chilled Water Temperatures at Different Average Indoor Room Dry-Bulb-Temperatures.

Numerical Results

Numerical simulations were carried out on six different slab cases and conditions, Case [A] is based on 15.55 m/m² TAB that utilize 23.00C water temperature as presented in Figures 15, 16, and 17, while Figures 18, 19, and 20 illustrate the same conditions to show the heat transfer coefficient but without any subjected heat on the exposed slab surface, similar to partitioned slab between typical floors.

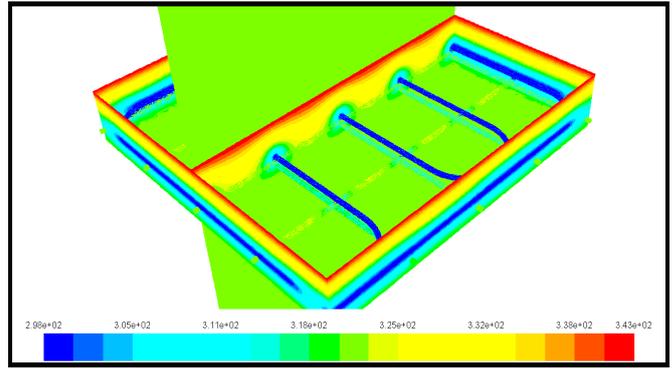


Figure 15 Prediction [B] for Contours of Total Temperature Distributions in °K

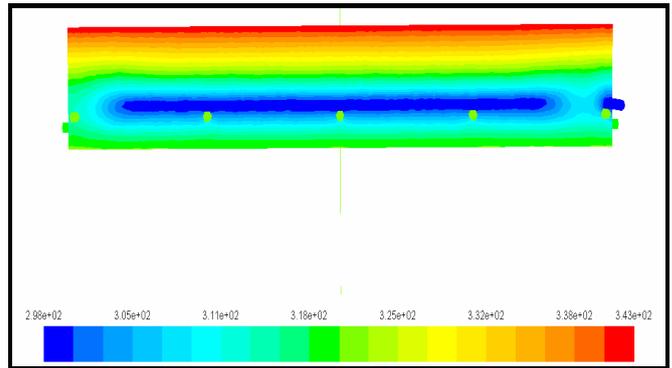


Figure 16 Prediction [B] for Contours of Temperatures @ Middle Section in °K

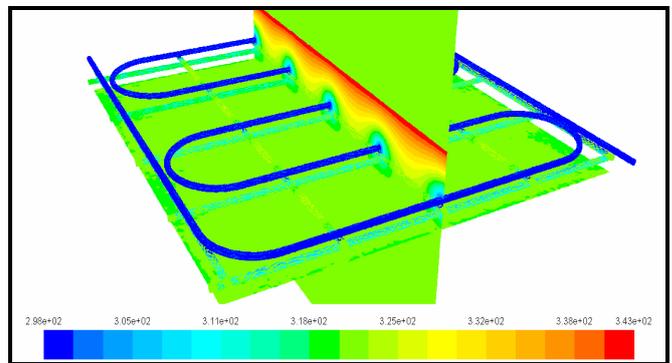


Figure 17 Prediction [B] for Contours of Total Temperatures @ Middle Section in °K

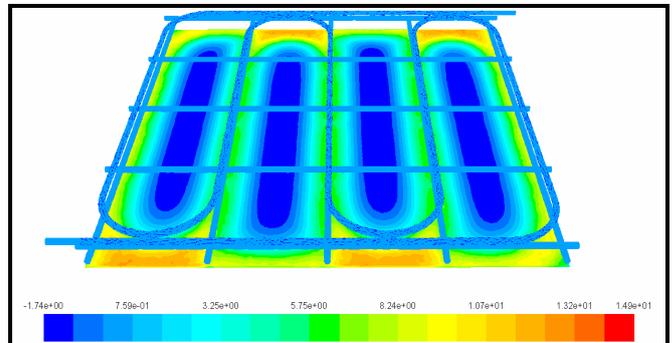


Figure 18 Prediction [B] for Surface Heat Transfer Coefficient @ Lower Zone in W/m².°K

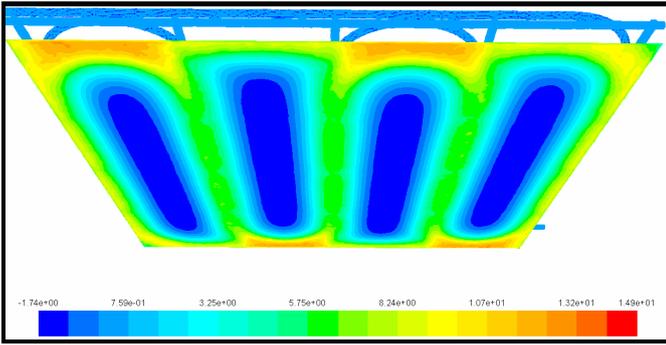


Figure 19 Prediction [B] for Surface Heat Transfer Coefficient @ Lower Zone in $W/m^2 \cdot ^\circ K$

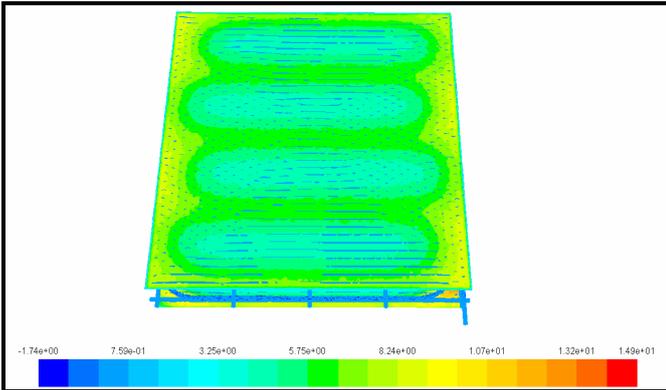


Figure 20 Prediction [B] for Surface Heat Transfer Coefficient @ Lower Zone in $W/m^2 \cdot ^\circ K$

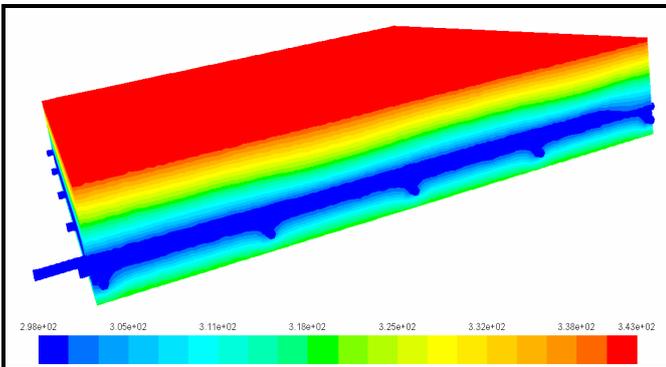


Figure 21 Prediction [C] for Contours of Total Temperature Distributions in $^\circ K$

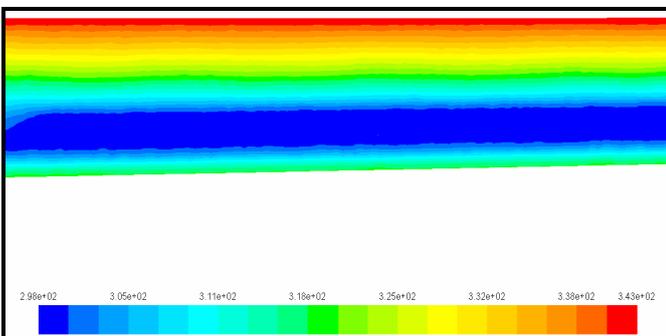


Figure 22 Prediction [C] for Contours of Temperature Distributions @ Mid-Section in $^\circ K$

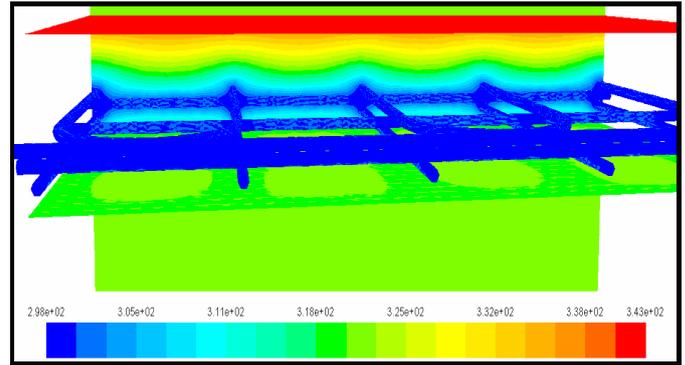


Figure 23 Prediction [C] for Contours of Temperature Distributions @ Mid-Section in $^\circ K$

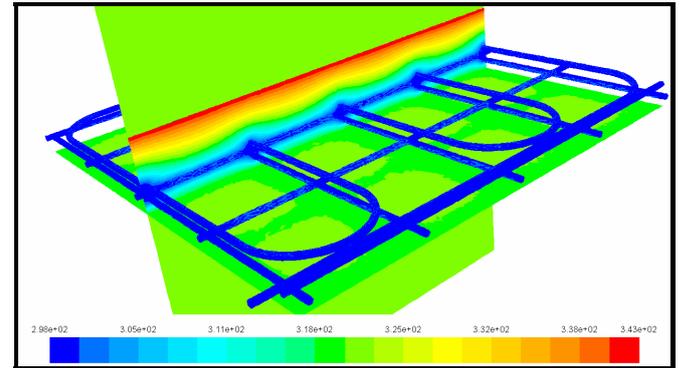


Figure 24 Prediction [C] for Contours of Temperature Distributions @ Mid-Section in $^\circ K$

CONCLUSIONS

It is well understood that there are many researches needs to be implemented on the methods of measurements especially for the separation between reinforced steel bars, upper and lower slab parts, and the conductive layer where the pipes are located. Further detailed experimental work is in progress for optimization of the TABs design. Finally, CFD is a powerful tool for these investigations with experimental assessments.

The work presented in this paper has many implications for the use of TABs. It has been believed that it was not possible to apply TABs exposed roofs. Although three years were spent for experimental investigations and the validating of such gained data from this test facilities but it still needs more controlling developments regarding to error analyses and measuring uncertainties. Present study declared that in order for TABs to work in tropic regions, especially at Upper-Egypt the following must be considered, (1) Keep internal cooling loads as low as possible, (2) Do not use TABs for the exposed building envelope, (3) Provide large surface areas with exposed concrete, (4) Adopt the daily temperature drifts i.e., lower end of comfort zone at morning and upper end of the comfort zone at afternoon, (5) Always apply the concept of high temperature cooling.

The CCRS shows results well adapted to different contexts. Residential buildings usually require about 175 to 200 w/m^2 of cooling capacity. This cooling capacity can be not easily

achieved through chilled water flow rate ranged $0.01 \text{ m}^3/\text{h}/\text{m}^2$ to $0.04 \text{ m}^3/\text{h}/\text{m}^2$ and water temperature ranging between 14.0°C and 20°C in summer. This temperature range prevents condensation risks in cooling at hot and dry climates. It was concluded that slab absorbed cooling capacities is roughly proportional to the temperature difference between the chilled water and the room dry-bulb. So, by choosing suitable chilled water temperature, cooling capacity can be adjusted as in order to obtain $40 \text{ W}/\text{m}^2$ cooling capacity in a room required to be at 27°C , then chilled water temperatures shall kept at 17°C .

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