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146. Thermo Active Building Systems; Technology, Application and Energy Efficiency for Buildings in Pakistan.

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Abstract

Living in a world dominated by increasing energy usage and diminishing fossil fuels, the current energy consumption in buildings for thermal comfort stands at a record 30% of the total energy consumption in the world. This has forced researchers and engineers to pursue building innovations required for energy efficiency and reducing the heating/cooling load in general. Furthermore, in the context of Pakistan, these endeavours are of immense value, where there are extreme climates in both summer and winter and the energy sources for maintaining thermal comfort in buildings, which include electricity and gas, are often insufficient to meet the demand.Of the emerging technologies in building innovations, Thermo Active Building Systems (TABS) seems an area where there are research shortcomings for their application to general building usage.Most of the literature review and existing research reveals that the existing information needs to be simplified in analysis and interpretation as well as application. Therefore, this research was aimed to come with a simplified design methodology in the most economical way possible and make practically feasible and low energy consumption TABS based buildings possible in Pakistan and the entire world.Based on hydronic Thermal Activation techniques, HDPE PEX water filled pipes were therefore tested in concrete samples and the thermal fields were analyzed. The Thermal Activation techniques are extended to reinforced concrete slabs and a general pipe spacing and location within the slab for the maximum thermal effect is studied. Sensitive temperature measurement devices were procured for accurate and precise quantitative measurements and all known literature and effective technology were utilized in this research. These measurements have been analyzed and validated with repeated measurements and by using spreadsheet tools. Finally an equation is proposed which can be employed to ordinary concrete activated by PEX pipes. This research simplifies the assumptions and inaccuracies which arise from simulation studies in TRNSYS, and the results being based on physical measurements are far more reliable instead of hypothetical circuit based analogies.This research is a hard work of over 8 months of time and effort. It is also hoped that this work would be a very useful contribution to the technical research in the construction industry and in the move towards Zero Energy Buildings.

Keywords: *Thermo Active Building Systems (TABS); Energy Efficient Buildings; Thermal Comfort.*

1. Introduction

1.1 Energy Efficient Buildings and the Move towards Innovation

Due to the increasing energy consumption worldwide, and the increasing dependence on fossil fuels for maintaining thermal comfort in buildings, the energy costs per building have also been on the rise [1]. Researches and Engineers alike are in search for alternative methods to increase the energy efficiency of buildings by innovative constructions, improved insulations or a combination of the two. There also have been numerous efforts to identify and replace some existing building systems with newer ones and with a lower energy consumption, some of which have been successful [2]. Of these emerging technologies, the most notable ones include floor heating and cooling systems by the use of hydronic pipes also referred to as Thermally Activated Building Systems (TABS).

1.2 Thermally Activated Building Systems

TABS is an innovation to the interior thermal comfort technology which is based on heating and cooling of thermal mass or the building structural components in itself [3,4]. This is in contrast to the conventional Air conditioning and Heating Systems which only heat/cool the air inside a building and are entirely air based. Since air has a very low thermal inertia, small changes in the outdoor temperatures can affect the thermal performance and the air temperature can rise or fall very soon after the HVAC source is turned off.

Building elements, especially the ones having a larger surface area for instance; slabs, floors and walls have a relatively higher thermal inertia [5]. If a slab is heated or cooled, it retains that thermal characteristic for a large amount of time and also influences the surrounding air temperature. In the present day, while the TAB systems are still developing most of the usage of this technology is to supplement the HVAC systems and decrease the heating/cooling load in order to minimize the energy input for the running of the conventional HVAC systems. A number of different models and performance evaluations have been proposed in the past two decades with still a lot of unknowns yet to be determined [6]. Simulation studies have been carried out in large using Resistance-Capacitance circuit network analysis, owing to the unpredictable Three-Dimensional heat transfer and dissipation in water based hydronic TABS [3].
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It is of interest to determine whether the use of TABS or hydronic heating systems alone can replace the HVAC systems and provide a better temperature control of the Activated Building element. In this way, the building component could be heated to such a temperature that it interacts with the volume of air inside the confined room and indirectly achieve an air temperature based on known thermal comfort conditions for a given climate [7]. This idea is illustrated in Fig. 1.

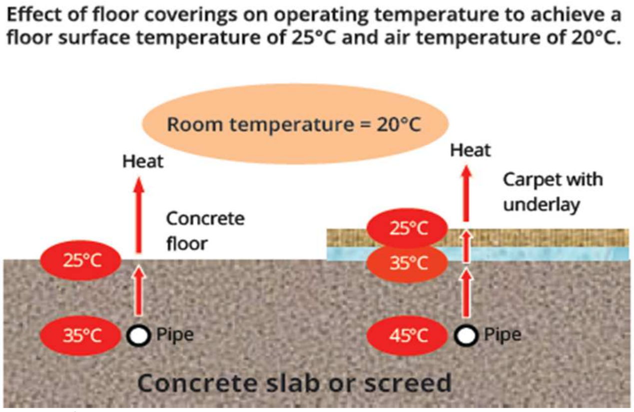


Fig. 1. Interaction of Concrete Slab Temperature with Room Air Temperature in TABS [5].

1.3 Thermal Conductivity of Involved Materials

TABS (Thermally Activated Building Systems) used in recent times are generally building elements activated by hydronic pipe systems. In case of concrete slabs, pipes are embedded into the concrete slab at a number of different possible positions. Sometimes hollow core slabs are used instead of solid slab for integral insulation or to create a thermal barrier between two interfaces of the slab. The most employed piping materials in the present day market are; Copper, PVC (Poly-Vinyl Chloride), CPVC (Chlorinated Poly-Vinyl Chloride), PEX (Cross Linked Poly-Ethylene), PE (Poly-Ethylene) and Steel [8]. Out of these, conducting metal pipes are disregarded in TABS because of condensation concerns and its effect on the relative humidity inside the building, when used for cooling and also for financial reasons. Furthermore conductive pipes increase the thermal conductivity of concrete in a region where they are placed and they lose thermal energy as soon as they gain them [9]. HDPE (High Density Poly-Ethylene) PEX pipes have a better thermal performance in hydronic systems and a higher thermal conductivity of around 0.5W/mK compared to other non-conducting materials which makes them suitable for use in TABS [8].
The performance and thermal behavior of hydronic heating and cooling systems using HDPE PEX pipes in concrete mass has been of interest in the building industry [4], especially concrete slab floors and ceilings.

1.4 Basic Mechanism of a Hydronic System

The basic working principle of hydronic pipe system involves the use of hot *Water*, a *circulation pump*, *water heater* working intermittently and a control panel called *manifold*.

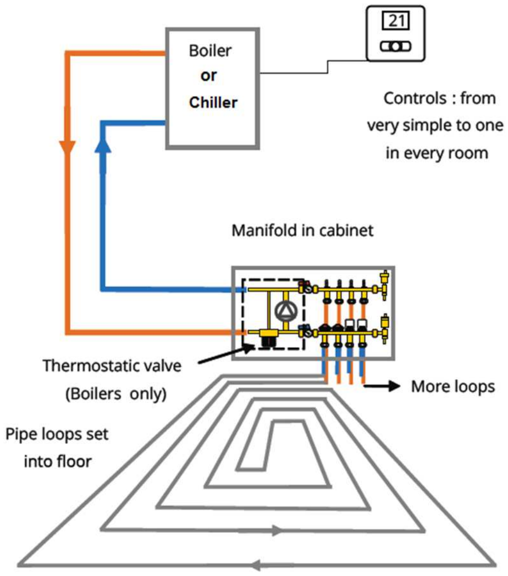


Fig. 2. Basic Layout of a Hydronic Heating System. (Introduction to Hydronic Underfloor Heating. Brochure, Central Heating Company, New Zealand.)

When hot water is introduced into the embedded pipe, the pipe wall absorbs the heat energy at a rate based upon the specific heat capacity of the pipe material. This heated pipe wall then transmits the heat directly by conduction to the layer of concrete right next to it. Once this layer is heated up, it transmits heat at a rate based on temperature difference to the next layer and so on.

In this research, an attempt has been made to examine the thermal effect of hydronic pipes embedded in concrete and highlight the region influenced by a single pipe. The region influenced by a single pipe will be referred to as the *Thermal Field* throughout the text. The test specimens and the subsequent methodology discussed in the coming sections are designed to understand the thermal effects in concrete and systematically arrive at conclusions which would be extended in obtaining other design parameters.

1.5 Influence of Thermal Conductivity in Concrete TABS

For a pipe carrying hot water to dissipate heat to the surrounding concrete, the rate of heat transfer will depend both upon the thermal conductivity of pipe material and the thermal conductivity of concrete surrounding the pipe. Concrete with higher thermal conductivity readily allows heat transmission and dissipation compared to the ones with lower thermal conductivity.

In ACI 122R-02 the thermal conductivity of concrete is calculated as a function of the Dry Density of the concrete mass [10].

In a Thermally Activated concrete slab, the heat is transmitted to the concrete based on the heat energy absorbed by the pipe wall of the embedded water carrying pipe. In this mode most of the heat transfer takes place via conduction only. The heat transfer through other modes including radiation and convection may exist but is far less to be reasonably ignored in a hydronic design analysis. Furthermore, if the specimen assembly is properly designed and the connections to pipes are properly insulated, the external effects on the results would be minimized. In most circumstances it is preferable to use pipes with lowest thermal conductivity for making connections exposed to the surrounding outside the slab. Some of the thermal conductivities of common piping materials in “Watts per meter Kelvin” are summarized in Table 1.

Table 1. Thermal Conductivity of Common Piping Materials

Piping	Material	Thermal Conductivity (W/mK)
Steel	Carbon Steel	54
Copper	Copper	401
PEX	Cross-linked High-Density Polyethylene	0.51
CPVC	Chlorinated Polyvinyl Chloride	0.14
PE	Polyethylene	0.38

2. Problem Statement

In recent years, since the introduction of the hydronic system, PEX (Cross linked Polyethylene) pipes have been extensively used in hydronic systems throughout the world. PEX pipes have a relatively low thermal conductivity of around 0.5W/mK and compared to metals like copper and steel, there is a general perception that PEX would underperform in a hydronic system which is primarily based on thermal conduction, or that the operating temperatures would need to be very high for a fair heat dissipation to concrete. Furthermore, it is also required that the pipes be placed at a distance which would help generate a uniform temperature on the surface of concrete.

This research is aimed to study the effect of a single hydronic pipe in a systematic manner and arrive at a conclusive result for the best thermal results based on effective pipe spacing and positioning. The expected outcomes will help us determine the required parameters for operating the hydronic system for a desired temperature of concrete.

3. Methodology

For a slab having pipes placed at a certain spacing, the temperature in a specific region of the slab is a function of the thermal fields generated by hydronic pipes embedded in it. If a single thermal field generated by a single hydronic pipe is known, the placement of pipes on centers and the positioning of the pipes could allow the interaction or overlap of adjacent thermal fields leading to a uniform temperature on the surface of the slab.

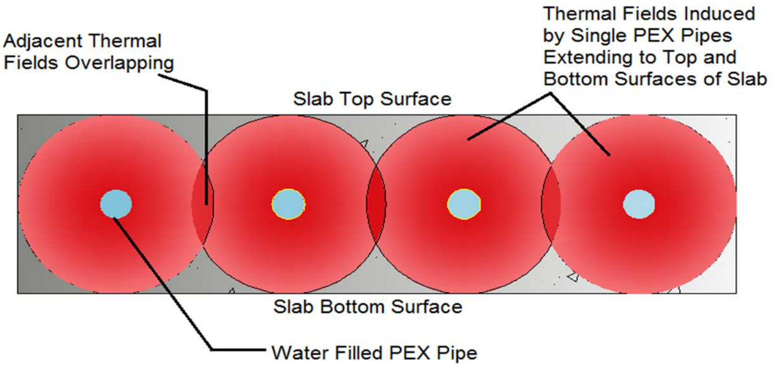


Fig. 3. Minimum Thermal Field Overlap in Slabs

If the thermal field of a single hydronic pipe is analyzed and the control parameters determined, it would be easier to design the same input parameters for a slab and the desired thermal effect would be obtained.

3.1 Standing Water Thermal Field Test

For determining the thermal field in concrete induced by a hot water carrying PEX pipe, a cylindrical test specimen having a diameter of 6 inches is constructed of exactly the same mix and proportions as the slab. The height of the test cylinder is kept at 18 inches to facilitate movement and allow easier connections and placements. A ¾ inch diameter PEX pipe is installed at the centre of the sample as shown in Fig. 4. Temperature thermocouple probes are inserted during casting located at fixed radial distances around the central PEX pipe. Touch sensing thermocouples are used for verifying and measuring temperatures at arbitrary distances and determining the thermal field generated by the hot water pipe.

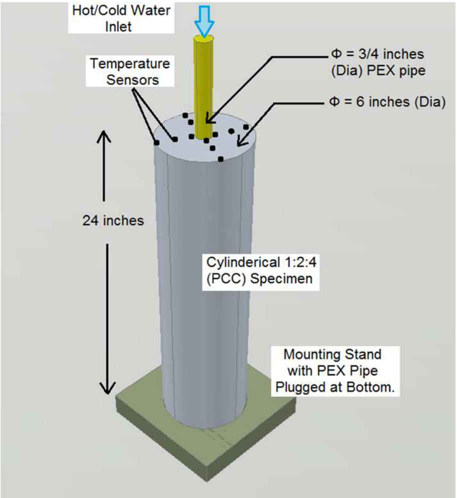


Fig. 4. Test Specimen for Thermal Field of a Single Pipe

The density of the sample is determined and the consequent thermal conductivity of the concrete is calculated using ACI 122R_02 [7], which came out to be 1.44 W/mK. The thermal conductivity of the concrete sample was also calculated from laboratory tests performed which came out to be 1.35 W/mK. In this research, however, we will use the calculated/assumed value of 1.44 W/mK.

The test cylinder was subjected to unsteady state conditions involving standing hot water by placing the cylinder vertically with the bottom end of the PEX pipe plugged and pouring water from the top until the pipe fills up to the level where it is fully embedded in concrete.

Hot water at different temperatures are poured into the upper end and allowed to stand, the surfaces of the specimen is covered for insulation and surrounding air draughts thereby reducing heat gain or loss to the surroundings. The experiment is repeated using similar conditions and the results averaged. A thermocouple probe is left into the pipe to measure the falling temperature of water. The temperature readings at various layers in the concrete is determined by the fixed thermocouples in conjunction with some touch sensing thermocouples, which after validation give the indication of the presence of the thermal field. The temperature measurements during a forty minute observation period are shown below:

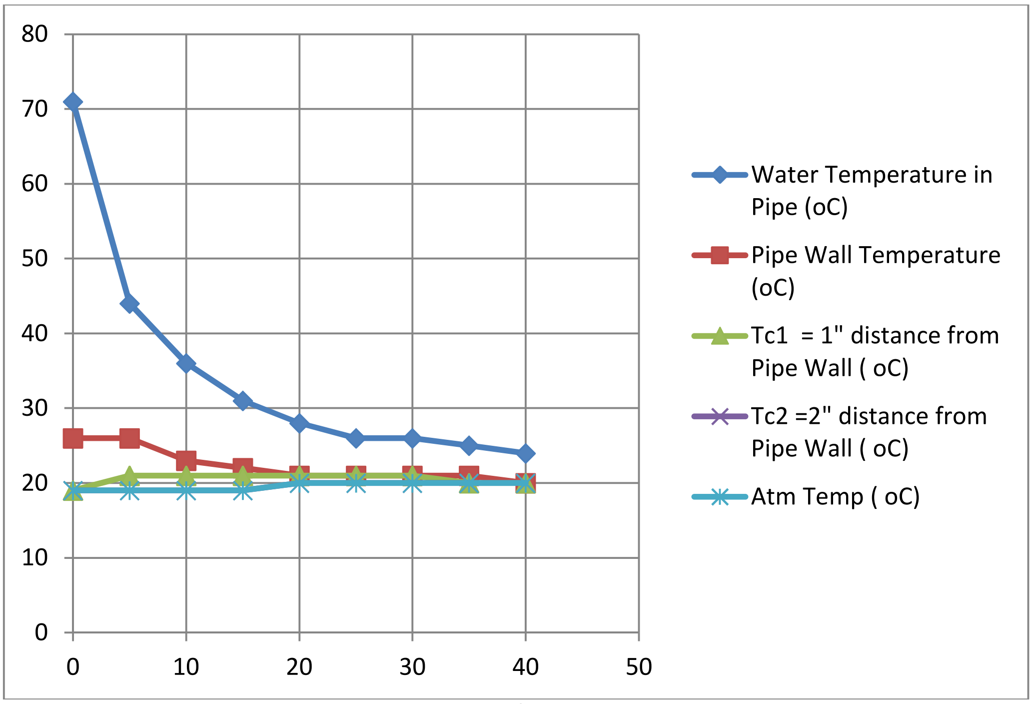


Fig. 5. Temperature Results from a Standing Water Test.

3.2 Circulating Water Thermal Field Test

In the next stage, the same sample is connected to a circulation pump with the same initial water temperature as the standing water test. The purpose is to see the difference in thermal fields induced by circulation of hot water and also to determine the impact if any, on the end results. The basic layout of the experimental assembly is shown in Fig. 6.

The water used in circulation is kept in an insulated reservoir and the initial supply temperature is fixed at 77°C. A pump is connected to the reservoir which pumps water out of the reservoir, passes it through the specimen and throws it back in the reservoir, thus a cyclic process is setup with a max flow rate of 15L/min circulation through the specimen. A flow variation valve is inserted in the piping to vary the flow rates.

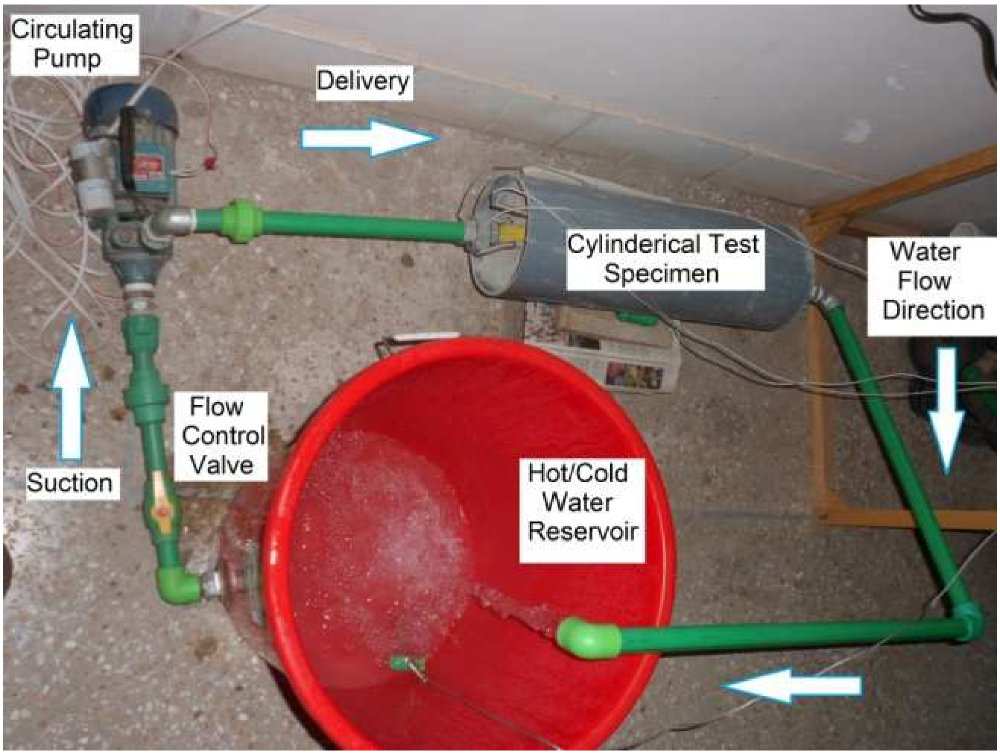


Fig. 6. Circulating Hot Water Testing Layout for the Specimen

During a one hour monitoring time, using a max flow rate of 15L/min the water temperature in the reservoir and the thermal field of the specimen is observed. The Temperature curves for circulating hot water test are shown below:

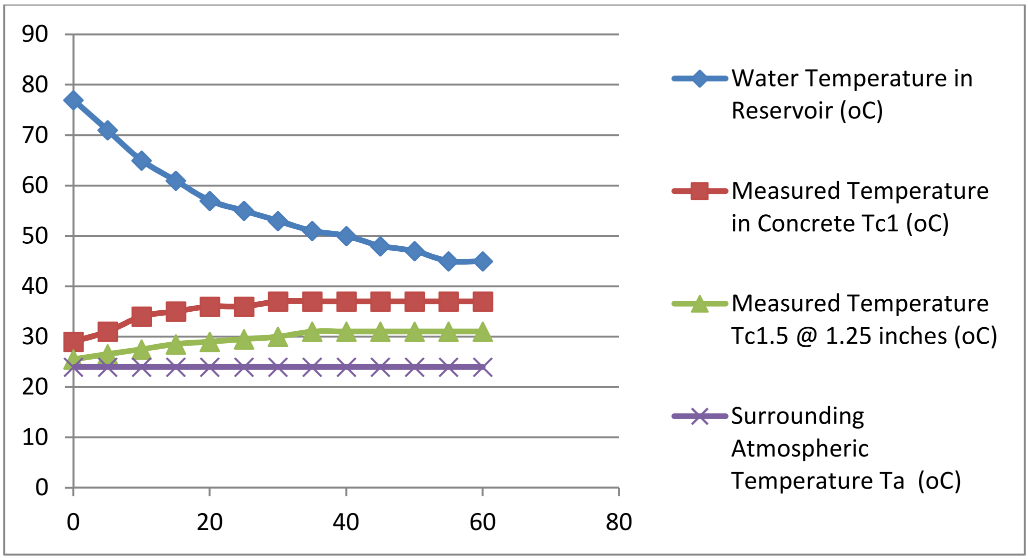


Fig. 7. Temperature Results from a Circulating Water Test.

3.3 Analysis of the Thermal Field Results

3.3.1. For Standing Water

The results from the standing hot water test gave an indication that the thermal field around the pipe was circumferentially distributed. The wall temperature measured right outside the PEX pipe was the same at all the four measurement positions. Further the rate of heat loss of water is rapid and water temperature reduced from a value of 77° C to 24° C in 30 minutes. The thermal field spreads into concrete to a distance of 1 inches from around the PEX pipe periphery. The temperature rise only shows a 3 degree Celsius rise from the initial outdoor temperature. At 1 inch distance from the pipe, out of the four readings taken, three measurement positions register the same reading with the fourth reading lagging by 1° C. Touch sensor thermometers could not indicate the existence of any thermal field beyond 1 inch. The temperature closer than 1 inch seemed consistent on all the four measurement positions with a value of 2°C greater at a 0.5 inch distance than the reading taken at a 1 inch distance. These results are illustrated in the Fig. below:

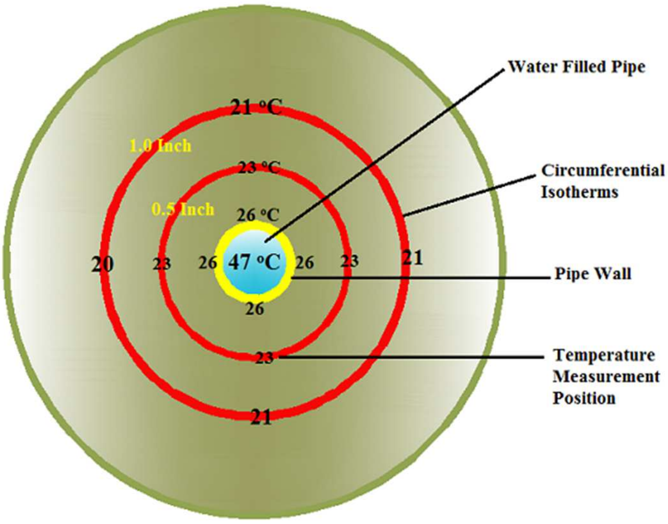


Fig. 8. Maximum Thermal Field in a Standing Water Test after allowing 77°C of water to stand for 5 minutes in a PEX Pipe.

3.3.2. For Circulating Water

For the circulating water the results show a faster rate of heat absorption into the pipe wall and higher temperature dissipation into concrete, the temperature rise occurs at a faster rate, although the flow rates seem to have very little influence on the heat dissipation unless the flow is reduced to about 5L/min.

The circumferential thermal isotherms are more prominent with the pipe wall temperature uniform at all the four measurement positions, the rise in the temperature of the wall is to about 43 °C within 10 minutes of starting time, which was 25 °C for the same amount of time in a standing water test.

The thermal field extends to 1.5 inches from the pipe periphery, with a max temperature rise in the 1 inch layer giving a value of 37 °C after 25 minutes of water circulation time. At a distance of 1.25 inches, the thermal effect reduces and one of the four readings measured differ by two degrees , with the average value of 30°C in the layer. At a distance of 1.5 inches the readings get inconsistent with two out of four readings differing by two or more degrees. The average Temperature is 27 °C at 1.5 inches from the PEX pipe wall, which is very close to the outdoor dry bulb temperature. No thermal field exists beyond 1.5 inches. The maximum effect is illustrated in the Fig. below:

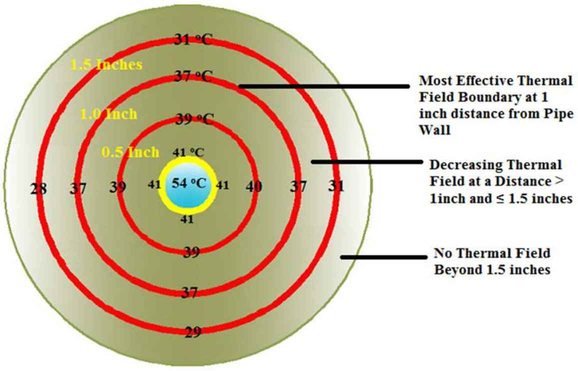


Fig. 9. Maximum Thermal Effect obtained after 30 minutes of Circulation. Starting water temperature is 77 °C.

3.4 Physical Analysis of Thermal Fields and Proposed Pipe Spacing

The max effect of a single hydronic pipe exists at 1 inches from the pipe wall and the thermal field is distributed circumferentially around it in the form of a concentric circle, with the pipe and the node of the thermal field having the same centre. At a distance of 1.5 the field is existent subject to the condition that the circulation is allowed and the flow rate exceeds 5L/min. Standing water has little influence on the temperature field in concrete and intermittent circulation is suggested for rapid temperature rise in concrete.

For an ideal concrete TAB System, the pipe should be positioned in the slab in such a way that the thermal field projects onto the slab surface. In this regard, for roof slab heating if the PEX pipes are placed above the bottom bars of steel reinforcement, it would be more effective subject to the condition that small diameter bars are used. For a clear cover of ¾ inches and a if 3/8 inches diameter bars are used as tension and distribution bars, the placement of pipe would be 1.5 inches above the slab surface. For larger diameter steel bars, the placement of pipes above the lower reinforcing cage would lead to the positioning being above the 1.5 inches mark. It is however perceived that the presence of steel with larger cross sectional areas, in the form of larger diameter bars, would enhance the thermal conductivity of concrete in that region to a sufficient extent to allow the thermal field to project to the bottom interface of the slab. This would negate the positioning factor and would help in surface temperature control.

For horizontal spacing between the pipes, the pipes should be placed 2.5 inches end to end for a rapid thermal effect. This is ideal because each thermal field extends 1.25 inches on either side of the pipe. For the minimum thermal field overlap, the horizontal clear spacing distance between each of the pipes should be kept at (1.25 x 2) = 2.5 inches.

A spacing of 3 inches is also possible but recommended for low heat output requirements. The results are summarized in Table 2.

Table 2. Summarized Results for Proposed Spacing of PEX Pipes within the Slab for Maximum Efficiency and Maximum Thermal Effect.

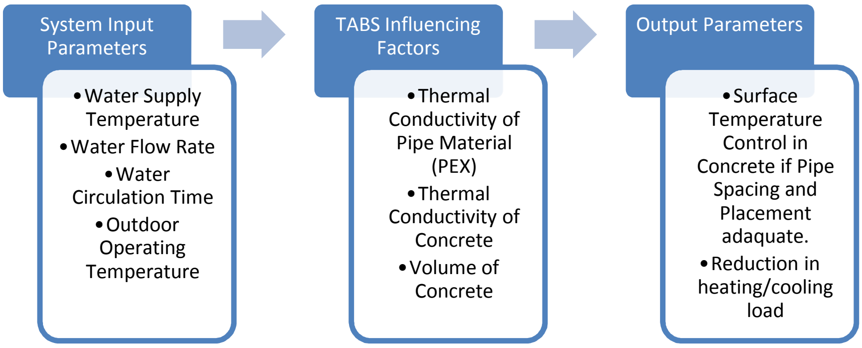
Parametric Position for PEX Pipes	Proposed Spacing within Slab (Inches)
Edge Distance of First Pipe	1.25
Horizontal Clear Spacing b/w Pipes	2.50
Clear Cover or Embedded Depth within the slab	1.25
Placement of Bottom Pipe Layers	On top of Reinforcement Cage
Centre-to-Centre Placement for ¾” Pipe	3.25
Maximum Possible Clear Spacing b/w Pipes	3.00

3.5 Numerical Study and Analysis of Thermal Fields for Determining Supply Water Temperature

In modelling and design applications it is imperative to achieve a predictable forecast for the thermal field inside the concrete slab. In that way the aim of the design becomes a desired surface temperature of the slab. The design parameters can be classified into three categories as shown in table 3.

A number of modelling equations relating the water temperature with other system parameters have been proposed in the last 10 years. Some of these models have been validated and have shown some degree of reliability. The only problem lies in the interpretation of proposed models. There are many design parameters involved in the model and most of which are relatively hard to determine. The reason behind this is that most of the models have been developed on the Resistance-Capacitance based electrical simulation studies. In some of the equations determining the values of Resistances and Heat Storage or Heat Capacitance is very hard to predict and generally involves the use of softwares such as TRNSYS and Simulink in MATLAB developed specifically for this purpose.

Table 3. Design Parameters for TABS



The most recent equations have been summarized in table 4 below [9] alongside the required parameters which show the degree of complexity involved in the interpretation of these equations:

Table 4. Modelling Equations for Different Design Parameters of Hydronic Systems [9].

Source	Proposed Equation	Required Parameters
Olesen and Dossi(2004)(a)	$T_{ws}=0.35(18-T_{oa})+18^{o}C$	T_{oa}=24 Hours Mean Outdoor Temp
Olesen and Dossi(2004)(b)	$T_{ws}=0.52(20-T_{oa})+20-1.6(T_{op}-22)\,^{o}C$	T_{oa}, T_{op}= Zone Operative Temperature
ISO 2012(a)	$T_{ws}= T_s- 1000Q(\check{R}+R_t)/h$	T_s=Temperature of Active Surface, $\check{R}$ = Resistance Between Tubing and Component Surface, R_t= Tubing Thermal Resistance for Constant Mass Flow Rate,Q=Specific Heat, h = hours of Pump Operation
ISO 2012(b)	$T_s= T_{rsp} + Q$	T_{rsp}= Room Operative Set Point Temperature, Q
Gwerder et al(2008)	$T_{ws} = T_{rsp}+(R_t+\check{R})(T_{oa}-T_{rsp})/R_f+(R_t+\check{R})q_{ub}$	R_f= Thermal Resistance of the Building Envelope, q_{ub}=Upper bound steady state internal and solar heat gain, T_{rsp}, T_{oa}, R_t, $\check{R}$

As seen in the table, the above proposed equations involve complex parameters to be determined before any prediction about supply water temperature can be done.

3.6 Simplified Equation for Water Supply Temperature for a Desired Surface Temperature based on the Heating Curve

To simplify this process and propose a simple equation for a desired surface temperature regarding the heating curve, the input parameters are compared with the various concrete temperatures obtained. Spreadsheet tools are put into use and equations for different variables are found using trend lines. It is seen that most of the plots are obtained in the form of non linear curves with an unpredictable analysis. When these parameters are retested for validation there are errors of differing magnitude in the results obtained. Most of the input parameters such as input water supply, flow rates, heat energy absorbed by pipe wall etc are plotted against the obtained temperature of concrete.

It was however, observed that if *Temperature Head* T_h (which is the difference of Water Supply

Temperature T_w and Surrounding Atmospheric Temperature T_a) i.e. ($T_w - T_a$) is plotted against the induced temperature in concrete in the max thermal field region of 1 inch i.e. T_{c1}, and the resulting graph is interpolated by a linear trend line, the results show great resemblance to the measured values with greater accuracy.

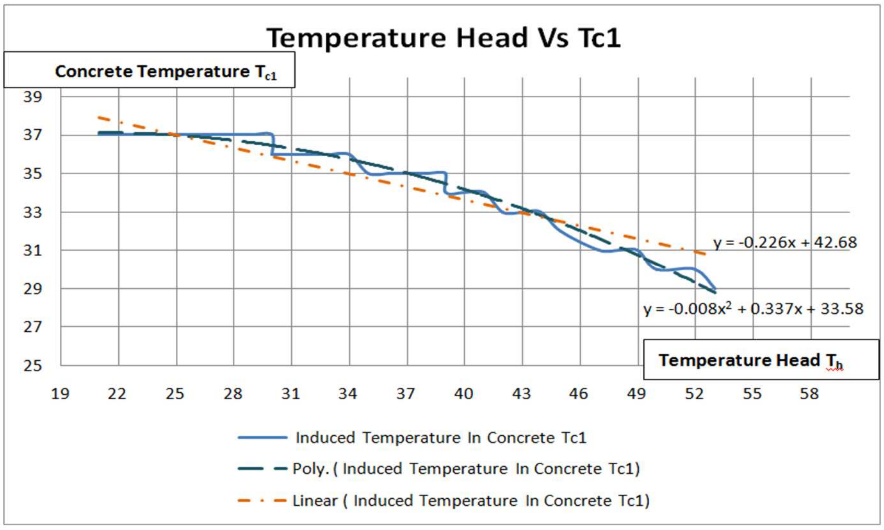


Fig. 10. Interpolation of Measured values with Linear and Polynomial Trend Lines.

The experimental testing was repeated at three different times of the day; morning, afternoon and evening, during which the test sample was placed outdoors for different initial concrete temperatures. The specimen was then tested in circulation mode. It was observed that the concrete temperatures attained within the thermal field agreed well with the following linear equation:

$$T_{c1} = -0.226(T_w - T_a) + 42.68 \tag{1}$$

The negative slope here is a function of the rate of heat dissipation into concrete based on certain input parameters such as input water supply temperature, flow rates, specific heat capacity and thermal conductivity of the pipe material, thermal conductivity of concrete etc. Furthermore, it is expected that similar concrete TABS with similar input conditions would have the same rate of heat dissipation and thus the same slope value in the above equation.

Rearranging the terms for input parameter of water supply temperature T_w, the equation becomes:

$$T_w = T_a - 4.38\, T_{c1} + 187.54 \tag{2}$$

For the quadratic equation of the trend line:

$$T_{c1} = -0.008(T_w - T_a)^2 + 0.337\,(T_w - T_a) + 33.58 \tag{3}$$

By this equation the Required Temperature rise in concrete with a given water supply shows very good agreement with the experimental values, however when this equation is simplified and solved for T_w, the resulting solution leads to complex roots.

It is therefore seen that Equation 1 and Equation 2 can be used as empirical equations for design calculations in similar setups with concrete having density closer to 150lb/ft^3 or having a thermal conductivity of 1.44 W/mK provided that a PEX pipe having a thermal conductivity of 0.5 W/mK is used.

4. Conclusions

Concrete based TABS systems are the easiest to integrate and the heat transfer within the concrete elements is fairly well defined and predictable as was illustrated by the outcomes of the present research. The operational mechanism has proven to be energy efficient as well as result oriented which allows greater flexibility in maintaining thermal comfort and buffering incoming peak heating/cooling loads. Furthermore, based on the interpretation of the thermal field results, the placement and positioning of pipes govern the thermal heat dissipation. By placing the pipes at appropriate spaces and maintaining the clear spacing between the pipes at 2.5 inches, the surface temperature of concrete elements can be controlled by a specific supply water temperature which is allowed to circulate within the PEX pipes.

Based on the heating curves and the characteristic behaviour of concrete TABS having similar thermal conductivities, the design and operational criterions can be fulfilled and a greater degree of energy efficiency achieved.

Acknowledgements

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