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Thermal Performance Analysis of Functional Parameters of the Floor Heating System in Africa

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Abstract Buildings frequently utilize radiant heating floors because they offer benefits including effective use of space and homogeneous temperature distribution, which results in increased thermal comfort. The present work aims to investigate the perfect use of floor heating systems analytically and numerically with improved thermal performance to prove their efficiency in various African climates. The evaluation depends on the functional parameters of the heating system and particularly focuses on floor surface temperature to acquire the desired heat flux and the perfect supply water temperature. According to results, It is desirable to use floor coverings with low thermal resistance and should not exceed R = 0.15 m^2. K/W since it has considerable influence on the thermal efficiency of the underfloor heating components. The pipe diameter is suggested to be about 20 mm. By comparing pipe spacings of 15 mm and 30 mm, the difference in supply water temperature is approximately 7.4 C. The smaller the pipe spacing, the more energy it delivers and makes the floor much warmer while reducing heating time. Regarding the effect of pipe materials, PE-X is chosen for this study because of its low cost and resistance to corrosion and scaling. As the influence of these studied parameters on floor heating is remarkable, there is also the impact of the ambient temperature of each city on the floor heating efficiency. The proposed model can be applied and considered potentially beneficial and helpful to the control, and design of floor heating systems, and choosing the right heating source.

Keywords Functional Parameters, Floor Heating System, Supply Water Temperature, Surface Temperature, Transient Simulation, Parametric Study.

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1. Introduction

The use of floor heating systems has recently increased in many countries due to its benefits in terms of thermal comfort of occupants, energy-saving, and healthy habitats. They are considered one of the most energy-efficient systems to heat indoor spaces, and particularly in several applications, such as new residential and commercial buildings, industrial buildings, airports, or train stations, and even for defrosting ice on the roads [1]. The floor heating can be connected to many technologies (electricity, fuel oil, gas, geothermal energy, etc.) and combined with renewable energy sources such as solar energy [2]. It also allows a gain in living space since it does not require a radiator and provides thermal comfort superior to other types of heating because the heat is distributed evenly in the room horizontally and vertically.

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However, it is necessary to control the heat flux released from the floor surface to achieve good thermal comfort and avoid unwanted deformation of materials.

It is reasonable to classify floor heating system parameters into two types: internal and external working conditions. The temperature inside a concrete slab depends on several working conditions such as the pipe spacing, water inlet temperature, pipe diameter, and screed thickness. However, the external working conditions comprise ambient temperature[3].

Several studies examined the effect of design and operating conditions on the thermal performance of floor heating systems. In six Moroccan climatic zones, S.Oubenmoh et al.[4] provide a comprehensive model of the solar radiant heating systems. The research proves that the system can adjust to Morocco's environment, which has a solar fraction ranging from 65% to 87%. According to the findings of the economic analysis, the system payback period was between 7 and 13 years.

Ricardo M. S. F. Almeida et al.[5] carried out a three-panel experiment using a radiant floor system of comparable dimensions, shapes, and tubes with various screed mortar formulas. The results demonstrated that the system's efficiency is appropriately impacted by the improved screed mortar. Additionally, a 3D model of transient heat transmission was verified using the results of experiments. When employing various floor coverings options including cork, wood, ceramics, and linoleum, changes in surface temperature of about 15% are evident. Moreover, Dengjia Wang et al.[6] showed that the pipe spacing has a significant impact on the preheating time and pipe thickness has a significant effect on the heat release time.

Sattari et al.[7] etablished that design parameters such as the thickness and type of hydraulic circuit have a greater influence on the performance of underfloor heating system. The pipe diameter has no effect on the ambient temperature inside the building.

A numerical simulation was performed by Laafer et al.[8] to study how the temperature of the heat-transfer fluid operating in the floor heating system affected the temperature of the indoor air as well as how surface radiosity affected the temperature profile of the indoor air. It was demonstrated that raising the temperature of the heating transfer fluid from 30 to 50 °C led to a temperature of about 15.1 °C at a height of 50 cm within the room. Qing-qing Li et al. [9] showed that floor construction and system characteristics can affect the floor surface temperature. The proposed method allows an easy estimate of the distribution of the floor surface temperature and analyzes the impact of temperature on the environment.

S. Oubenmoh et al. [10] presented a 2D numerical simulation model based on the finite volume method, to study the influence of some parameters on the thermal behavior of underfloor heating systems such as water velocity, fluid inlet temperatures, and the shape of the pipes.

The aim of this study is to provide an approach based on the heat transfer process and to give insights into the potential design of floor heating systems in various African cities to calculate supply water temperature and heat flux released by floors heating systems. The results of this study can be employed for an estimate of significant parameters in the actual application and design of the underfloor heating system.

2. Methodology

2.1. Physical model

A large room was chosen as a suitable reference object. The building is located on the ground floor and corresponds to the most common building styles. It consists of two sides facing outward and in a southeast direction allowing the sun to shine directly from about 9 to 13 hours. Windows are placed in southerly directions to utilize solar radiation at a high rate.

As shown in figure 1, a network of pipes, modeled as two coaxial cylinders, is embedded in a screed layer. The floor surface can be PVC, marble, tiles, parquet, etc. Under the slab, an insulating layer thickness of 50mm is used in order to decrease heat loss to the bottom.

The room is heated by convection and radiation. the system transmits heat through long waves between

the building surfaces and from the top floor surface to the indoor air. Conduction is ensured by contact between the different layers of the floor.
The interior space (Ta) is maintained at 20 $°C$, which corresponds to the temperature of the interior air in winter and the outside temperature is -5.2$°C$, which presents the outside temperature in winter in Ifrane, Morocco.

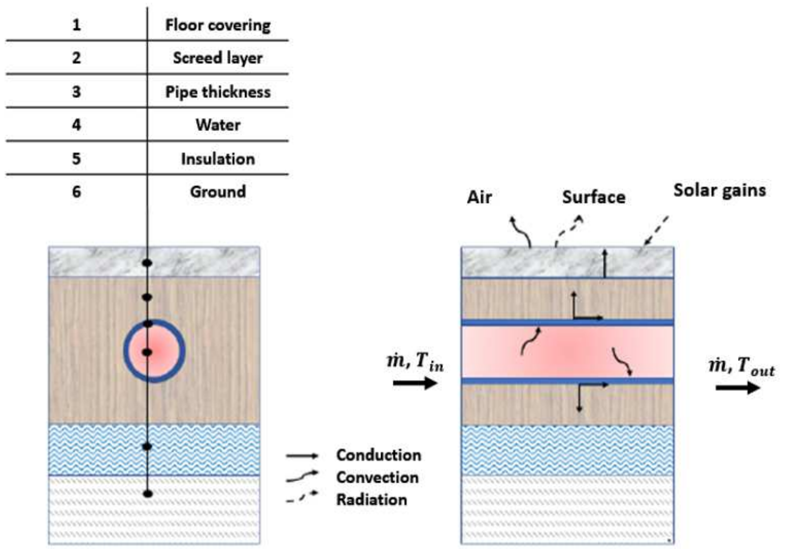


Figure 1. Heat transfer modes of an axial and longitudinal section of a heated floor.

- Floor covering

According to the most common values given in the respective standards, the system performance is examined through the various floor covering resistances but with variable thicknesses, Namely: R0=0(Without), R1=0.005 m^2. K/W (Marble), R2= 0.01 m^2. K/W (PVC, Linoleum), R3=0.02 m^2. K/W (Bluestone Slabs), R4=0.03 m^2. K/W (Mosaic parquet), R5=0.04 m^2. K/W (Terracotta on mortar bed), R6=0.06 m^2. K/W (Oakwood), R7=0.08 m^2. K/W (Parquet), R8=0.15 m^2. K/W (floor tile) and R9=0.24 m^2. K/W (Wool carpet). For all resistance values, the new water supply temperatures are calculated.

- Screed layer

This layer is a construction element that supports the mechanical stress, being a result of permissible loads, and thermal expansions (both screed and pipes). Its serves as a layer that transfers heat to the room. The screed layer used in this study is analyzed via different thicknesses from 30 mm up to 60 mm with a step of 5 mm. The choice of the screed material used is analyzed also. The thermal conductivity of cement mortar is 1.2W /m. K and for anhydrite is 2.5W /m. K.

- Pipes

Thermal inertia imposes a certain delay between the moment when water is supplied to the pipes and when the surface temperature changes. At the level of pipes, thermal inertia depends on several characteristics such as thermal conductivity, diameter, and spacing between pipes. The pipes used in this floor heating system are studied through different spacing such as 0.15m, 0.2m, 0.25m, and 0.3m and diameters namely: 20mm,18 mm, 16mm, and 14mm. To evaluate the thermal properties of pipes, three types of pipe materials are compared, namely cross-linked polyethylene (PEX), copper, and steel whose thermals conductivities are respectively 0.35W/m. K, 380W/m.K and 13.4W/m. K.

- Weather

The main climatic parameters that present a significant influence on the design of solar energy conversion systems, are solar radiation, ambient temperature, humidity, and wind speed. The article offers a comparative analysis of meteorological data for five African cities such as Ifrane (-5.2°C), Cairo (7°C), Southerland (0°C, Masvingo (5.4°C) and Lesotho (0.2°C) generated by the METEONORM software to assess the effect of ambient temperature on the supply water temperature.

2.2. Mathematical formulation

The basic equations for the appropriate mathematical formulation for this work are given in this section. These equations regard parameter definitions, energy balances, and the necessity to evaluate calculated results. Regarding the total heat flux released from the floor surface, it depends on the convective heat flux Qc and radiative heat flux Qr terms as shown in the equation below:

$$Q_{Tot} = Q_c + Q_r \tag{1}$$

Depending on the average unheated surface temperature (Aust), the heat exchange with indoor surfaces of the room is expressed in the equation below:

$$Q_r = 5 * 10^{-8} * [(t_{floor} + 273.15)^4 - (AUST + 273.15)^4] \tag{2}$$

The 2nd term of the flux equation is the convective heat exchange presented in the equation below by the corresponding heat exchange coefficient (hc) and the room air temperature (Ta):

$$Q_c = 2.13 * |(t_{floor} - T_a)|^{0.31} * (t_{floor} - T_a) \tag{3}$$

For specific heat flux released and the supply water temperature Twater, we can express it by using the equation below according to the thermal resistance of the pipe wall per unit pipe spacing in a hydronic system and pipe spacing Ps [11]:

$$T_{water,in} = t_d + (Q_{Tot} + Q_b) * P_s * R_t \tag{4}$$

where Td is the pipe average surface temperature.

To determine the supply water temperature, we must calculate the thermal resistance of the active layer firstly. The thermal resistance of the panel influences the heat transfer to the tube, which reduces the thermal resistance and allows for good heat transfer. The equation below presents the thermal resistance of the panel [11]:

$$R_u = R_t * P_s + R_s * P_s + R_p * R_c \tag{5}$$

where Rp, Rs, Rc, and Ru present respectively the thermal resistance of the panel body, thermal resistance between the panel body and the pipe per unit of tube spacing, the thermal resistance of the floor covering of the panel, and the total thermal resistance of the panel.

3. Results and discussion

To estimate the heat flux released and supply water temperature, the properties and the size of the underfloor heating system are designated firstly. The results of the functional parameters are presented below.

3.1. Variation of thermal resistance of floor covering

The floor covering materials can be a personal choice (interior design, architecture, texture, etc.) able to make important impacts on the thermal performance of the floor heating system. This layer represents the contact zone between the ground and the air layer and is the major responsible for the direct heat transfer to the room. In the analysis of Figure 2, it appears that an increase of the floor covering resistance leads to an increase in the supply water temperature as well as the heating load. Indeed, all floor coverings from R = 0 m^2 K/W at R = 0.15 m^2. K/W requires lower supply temperatures between 36 °C and 55 °C to achieve the normalized surface temperature of 29°C. For Floor coverings above 0.15 m.^{2} K / W such as sheet viny, wood products or carpet can also be used, but it isolates the floor and hinder the efficiency of the entire floor heating system.
The increased resistance of the floor coverings has a similar effect in increasing the heating demand on the waterside of the floor heating. It affects the size and installation of heating, which will lead to larger heating installations than necessary if the resistance of the flooring was reduced to a minimum.
In this case, due to the significant impact of the floor covering on the thermal efficiency of the underfloor heating elements, it is preferable to use materials with small thermal resistance and should not exceed R = 0.15 m^2. K / W.

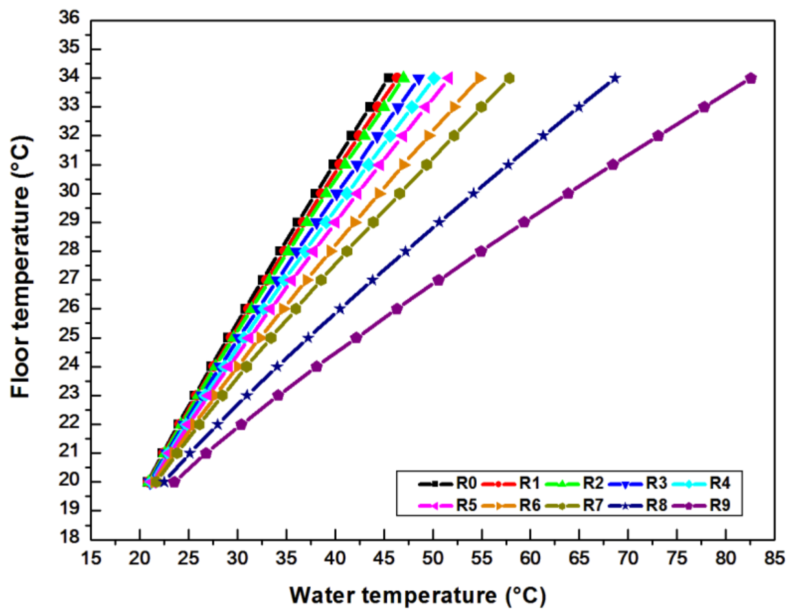


Figure 2. Variation of thermal resistance of floor covering and its impact on supply water temperature.

3.2. Impact of thickness of screed layer on floor heating system

On the other hand, figure 3 shows that the screed layer thickness has nearly no influence on the supply water temperature. For low surface temperatures, the water supply temperatures are relatively similar for different thicknesses of the screed layer. From the result, it is observed that for a surface temperature between 21 to 26°C the difference of the supply temperature for the seven screed layers is around 0.2°C, and exceeding 26°C the range becomes more 0.6°C. For example, the desired supply water temperature is 40,03°C for 30mm compared to 41,64°C for 50mm to reach the ground temperature of 29°C. However, the thinner the screed layer, the lower the water supply temperature. It should also be mentioned that the heat storage capacity increases with very thick layers. In this case, the heat flux cleared during the intermittent period will be slow relatively.

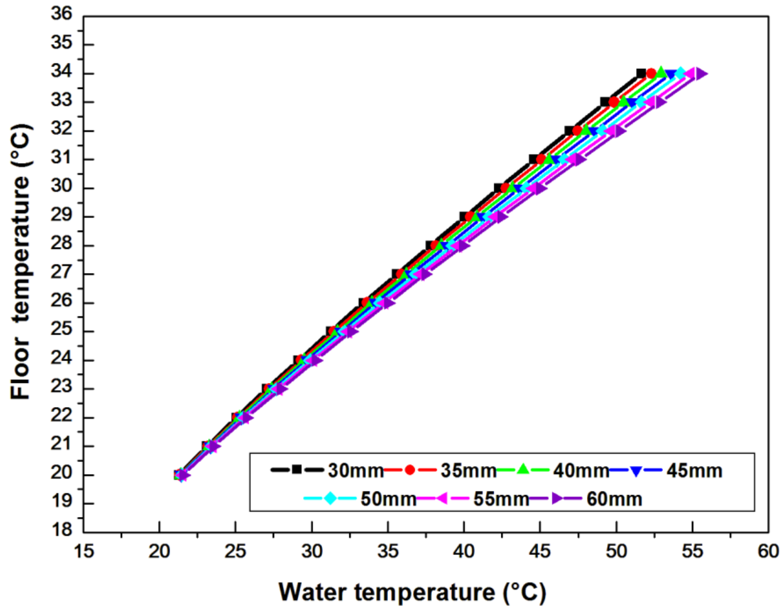


Figure 3. Effect of screed layer thickness on supply water temperature.

3.3. Comparison of screed layer materials

A quality screed makes it possible to ensure a faster rise in temperature of heating, a finer regulation of the temperature, and a homogeneous heat at all points of the rooms to be heated with better heating efficiency. They are used for all coatings and provide an optimal coating. These two types differ in terms of composition, technical characteristics, drying time as well as Warm-up delay. In figure 4 two types of fluid screed were compared, the cement screed and the anhydrite screed. From the result, it is observed that for a surface temperature between 21 to 26°C the range of the supply temperature for the two materials is between 0.1°C to 0.9°C and beyond 26°C the range becomes more 1.5°C. Compared to cement, the anhydrite layer provides reduced inertia, but this facilitates temperature regulation. It is the strongest coating and offers very low shrinkage.

3.4. Impact of pipe spacing on floor heating system

The figure 5 present the influence of pipe spacing on supply water temperature. A similar trend is observed for the four-pipe spacings. From the result, for a given floor surface heating effect, the supply temperature can be lowered with narrower pipe spacing. If a system is planned where a low supply temperature is desirable, e.g. When a heat pump is to be installed, it is suggested to select a narrower pipe spacing. If the supply temperature needs to be higher, a wider pipe spacing can be chosen, thus reducing initial material and laying costs. In other words, this studied parameter influences also the surface temperature distribution because the greater the spacing of the pipes, the clearer the shape of the heating pipe will be, which causes less temperature homogeneity [10]. The smaller the pipe spacing it provides more energy and makes the floor much warmer as well as it decreases the heating time.

3.5. Comparison of different pipe diameters and materials

Figure 6 shows the supply temperature needed to attain the floor surface by varying the pipe dimension. As shown, the pipe diameter has no significant impact on either water supply temperature or floor surface temperature. Increasing the diameter of pipes by 2mm causes the supply temperature to drop between

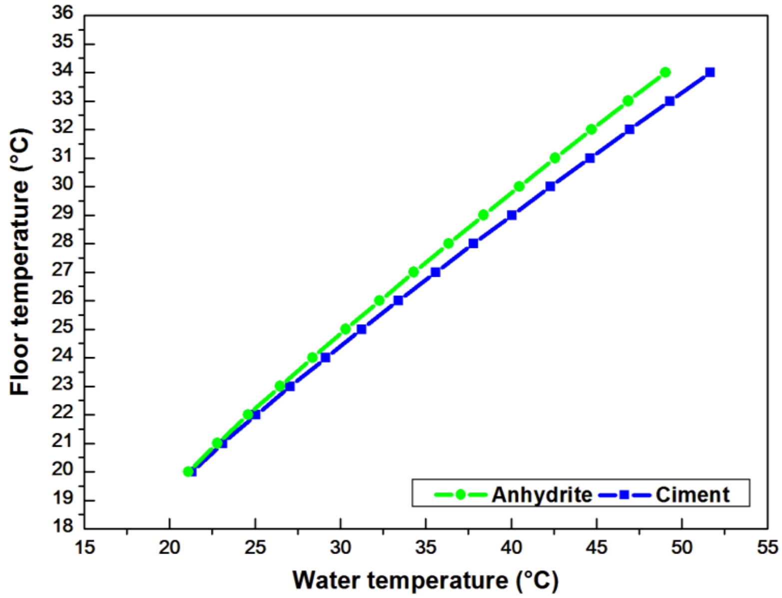


Figure 4. Comparison screed layer material on supply water temperature.

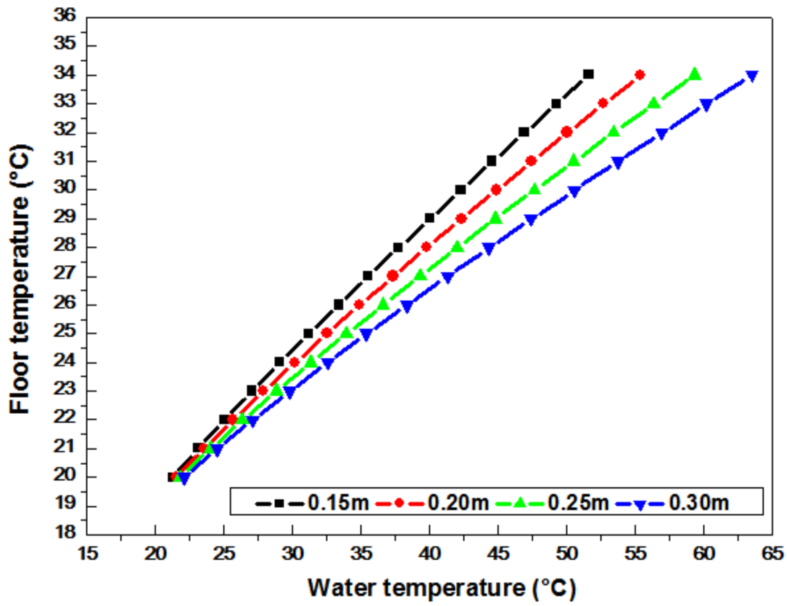
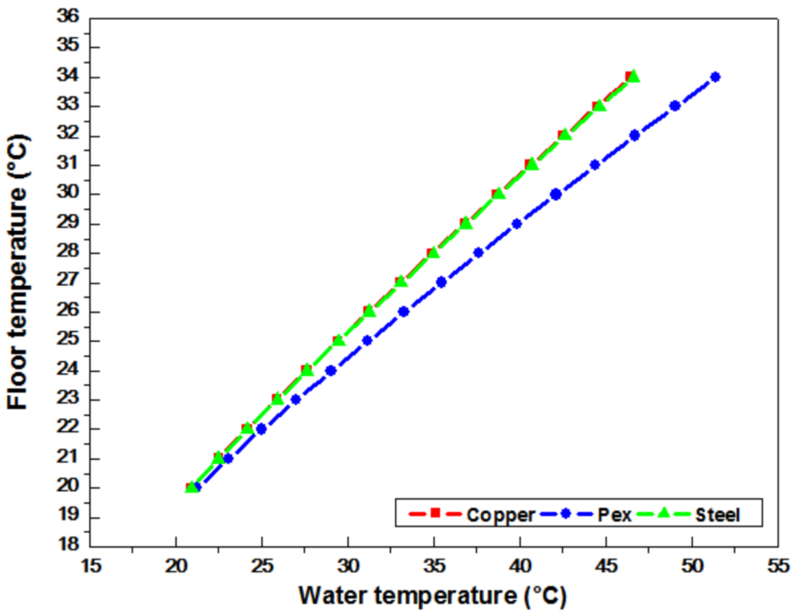


Figure 5. Impact of pipe spacing on supply water temperature.

0.1°C to 0.3°C. In practice, when the diameter of the pipe is large, there will be a negative impact on the structural behaviors of the whole system. This means that increasing the diameter improves the temperature difference, but the rate of change remains relatively slow. However, it is necessary to take into account the pipe diameter because a smaller diameter provides greater pressure in the tube, which requires more electricity consumption to operate the pumps. For a typical floor heating system, the diameter is suggested to be around 20mm.

The thermal properties of tubes present a crucial role in the floor heating system efficiency. To evaluate



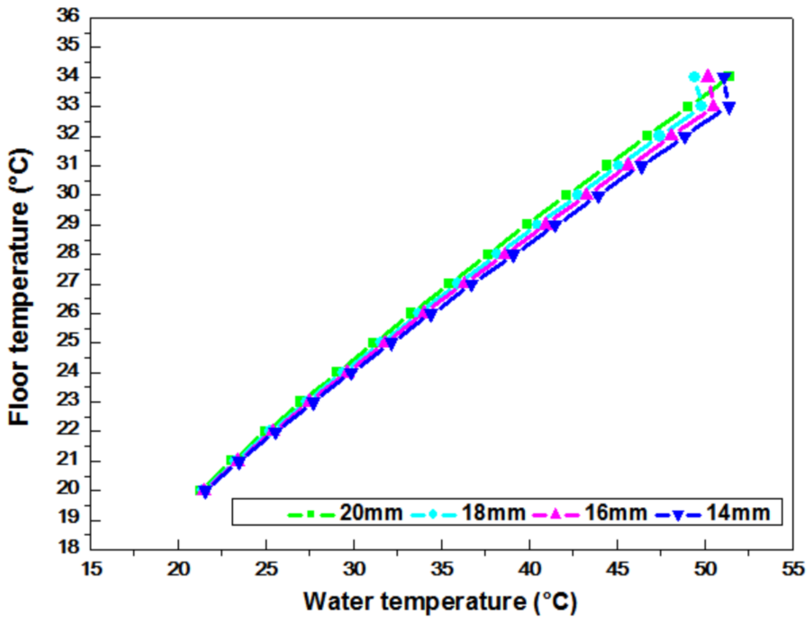


Figure 6. Impact of pipe materials (PE-X,copper and Steel) and pipe diameter on supply water temperature.

the effect, three pipe materials generally used in underfloor heating, namely copper, PE-X, and steel are compared. Figure 6 present the influence of tube materials on supply water temperature. A similar trend is observed for steel and copper pipes with a difference with PE-X of around 4°C to reach the ground temperature of 29°C.

Although copper and steel have important thermal conductivities compared to PE-X and can reach rapidly the floor surface temperature, it is necessary to take into account their high cost and the risk of

Table 1. Result of required supply water temperature of heat 96,58 W/m^2.

Component	Type	Value of basic parameters	Value of main parameters	Variation (°C)
Floor covering	Thermal resistance	0.04 W/m. K	0.08 W/m. K	3.86
Screed layer	Thickness	30 mm	40 mm	0,80
Pipe spacing	Thickness	150 m	300 m	7.423
Pipe diameter	Diameter	20 mm	16 mm	0.879

scaling over time. On the other hand, the PE-X presents the advantages of low cost, no welding, long lengths without connection as well as being resistant to corrosion and scaling.

3.6. Result of supply temperature of floor heating system

The heat flow released by the floor heating system, the supply water temperature, and the floor surface temperature are presented in figure 7 and table1. For example, in the case of two floors with different dimensions and characteristics that are likely to give identical heat flow Q, the supply water temperatures will be different from each other. Whereas if the main parameters (pipe spacing and floor cover) are different, then inevitably the relationship will be completely distinct from each other. However, the variation of other parameters such as the screed layer and pipe diameter may not make a significant difference to the desired supply water temperatures.

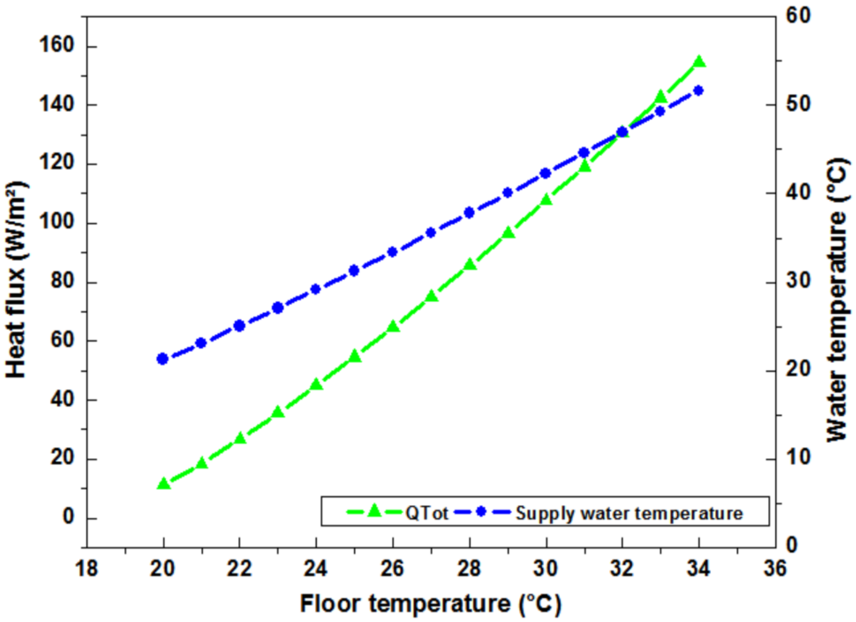


Figure 7. Linear relations between heat flux, supply water temperature and floor surface temperature.

3.7. Feasibility of a floor heating System in Africa

Africa has a range of climatic diversity such as the equatorial climate, the semi-desert climate, the humid and dry tropical climate, the subtropical climate of the highlands, and finally the desert climate. figure 8 present the supply water temperature of the five coldest cities in Africa during winter namely:

Cairo, Ifrane, Lesotho, Southerland, and Masvingo with the same floor covering thermal resistance. This parameter varies greatly from one city to another caused by meteorological conditions in each one. The analysis shows obviously that the ambient temperature affects the supply water temperature. For Southerland, the ambient temperature is around 0°C which requires a supply water temperature of 41,64 to reach the floor surface temperature required by the standard 11855 for a room of 29°C compared to 39,54°C in Cairo. Indeed, as long as the heating loads are very fluctuating and variable from one place to another and the supply water temperature depends also on the characteristic of the building which must be designed for each site according to its climatic conditions.

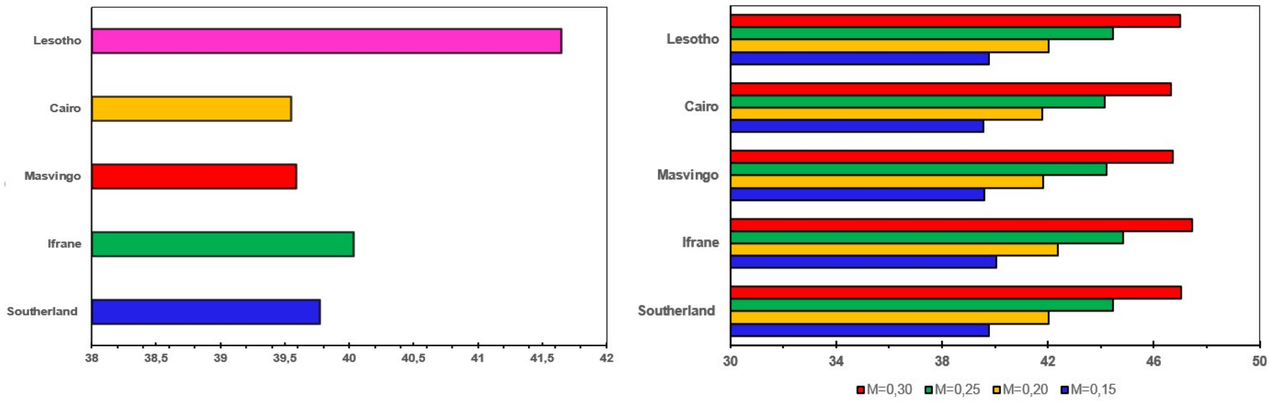


Figure 8. Supply water temperature for each city and for differents pipe spacing (Rcov=0.04 m^2.K/W).

3.8. Numerical simulation results and discussion

Separated from the analytical model studied previously, a commercial CFD software was chosen in this study based on the finite volume method. A set of numerical simulations are employed to simulate the thermal performance and the behavior between the integrated system and floor surface. The mathematical model for this system is given by the energy equation, the continuity equation, and the momentum conservation equation. To model the turbulence in the water field, the standard kepsilon model is used.
The analysis of the influence of the functional parameters on the thermal behavior allows to evaluate the potential, lead to higher performances and reduce the expenses. So, we studied here some parameter conditions and their influences on the thermal performance of the under-floor system and to make the correct choice according to the floor surface temperature.
The same composition of the previously studied system was chosen with an area of 2*2.43 m^2. The heating system is embedded with a diameter Di/Do of 16/20 mm as a counterflow spiral placed on expanded polystyrene panels with 15 cm spacing as shown in figure 9. The water velocity is chosen around 0.85 m/s. The water inlet velocity is fixed at 0.85 m/s. Among the various configurations of laying pipes used in the field for heating a room, the counterflow spiral configuration is the most efficient. It ensures better heat homogeneity of the floor and reduces pressure losses in the pipes [10].
The average core floor temperature is an important parameter of the system and has a significant influence on the floor surface temperature and on indoor thermal comfort. This parameter is analyzed for different supply water temperatures and for three pipe materials. The temperature profile at the floor core during three hours of heating is given in figure 10.
The floor temperature distributions during the heating process follow an increasing similar trend when the pipe water temperatures vary between 30°C to 45°C. In addition, with the increase in water temperature within the pipe, the surface temperature increases and becomes more significant when the ground temperature reaches a stable state.

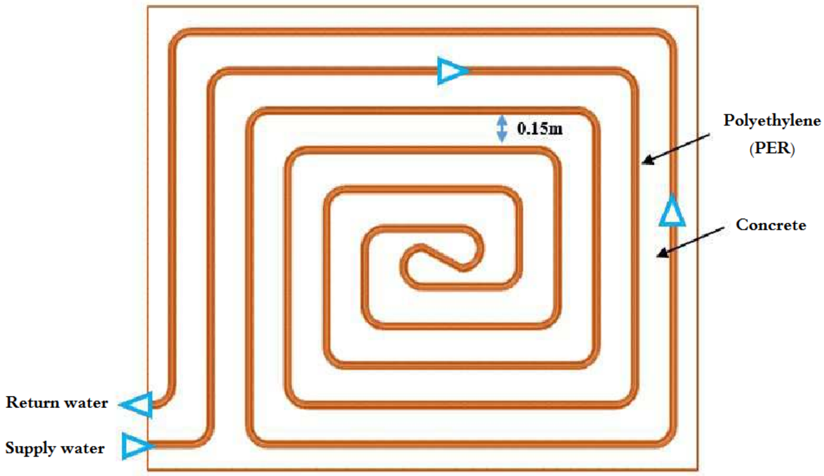


Figure 9. Plan view of counterflow spiral configuration.

Also, the total heating load is lower when the supply water temperature is around 40°C to 45°C. It takes considerably less time to achieve a target surface temperature of 29°C. This indicates that the heating time of the system can be significantly reduced by adjusting the temperature of the supply water temperature to a higher value.

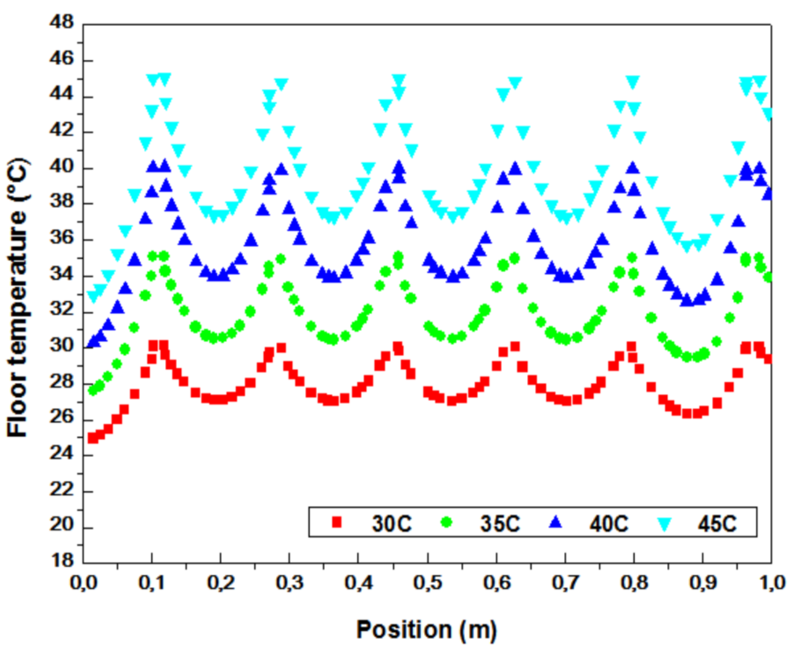


Figure 10. Supply water temperature variation on part of the panel surface

Obviously, as the supply water temperature rises in the system, the floor surface temperature presents an upward tendency. The lateral zones of the occupied surface compared to the areas with hot water circulation show colder temperatures as indicated in figure 11 when the water supply temperature is taken

45°C. The tube material obviously affects to some extent the floor surface temperature. The maximum average temperature obtained at x = 0.12m for copper is around 38.72 °C with a difference of 1.331 °C for PE-X and 0.03 °C for steel. The surface temperature differences for the same tube between PE-x and the other pipe materials were relatively remarkable, ranging from 1.5 to 2°C.

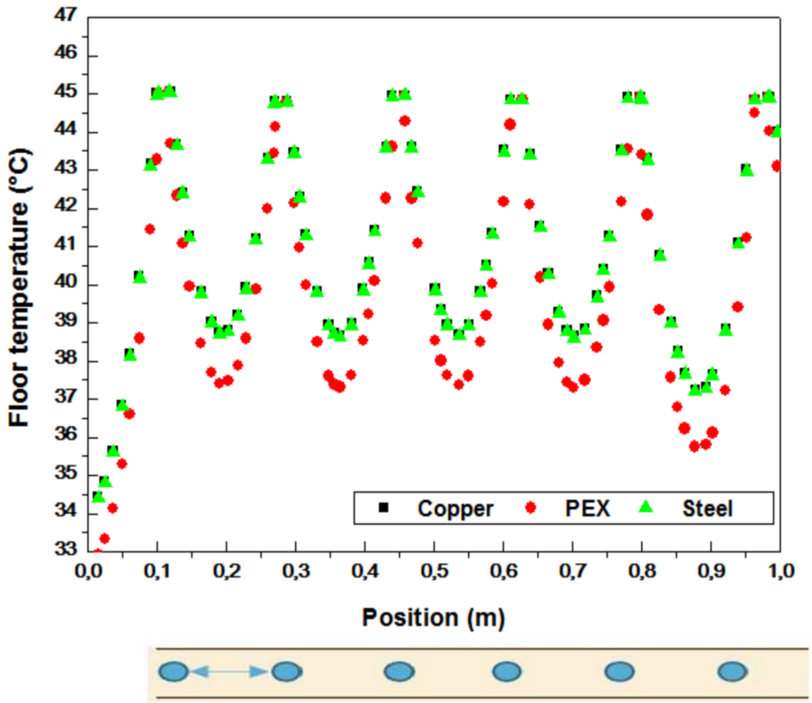


Figure 11. Temperature variation along the panel surface for three types of pipe materials.

The floor surface temperature distribution for three pipe materials is shown in figure 12. The relative magnitude of the temperature change is evident especially at the top surface, is significant because it will impact the comfort of the system. Both copper and steel atteint reach the ground temperature of 29°C in 2300s compared to polyethylene in 3000s. The top layer of heating pipes temperature is higher compared to neighboring regions and the average surface temperature during 3h of heating in copper, PE-X, and steel is respectively 33.61°C, 31.51°C, and 33.58°C.
PE-X is very often used for the realization of heated floors, although copper and steel conduct heat almost better because they are convenient to install. Indeed, the semi-rigid pipes are flexible, there is no welding to perform as with copper and steel pipes and they have a lifespan as long as this one.

4. Conclusion

The purpose of this paper is the right use of floor heating systems with improved thermal performance in order to prove their efficiency under different African climates. It also aims to evaluate the usage of simplified geometric models of underfloor heating systems and to use them in transient simulations.
A valid analytical model and simulation are presented to illustrate the effect functional parameters of the heating system and witch mainly focuses on floor surface temperature to acquire the desired heat flux and the perfect supply water temperature. The study relied on the three heat transfer mechanisms such as conduction, radiation, and convection.
It was concluded from the result that the characteristics parameter of underfloor heating systems has

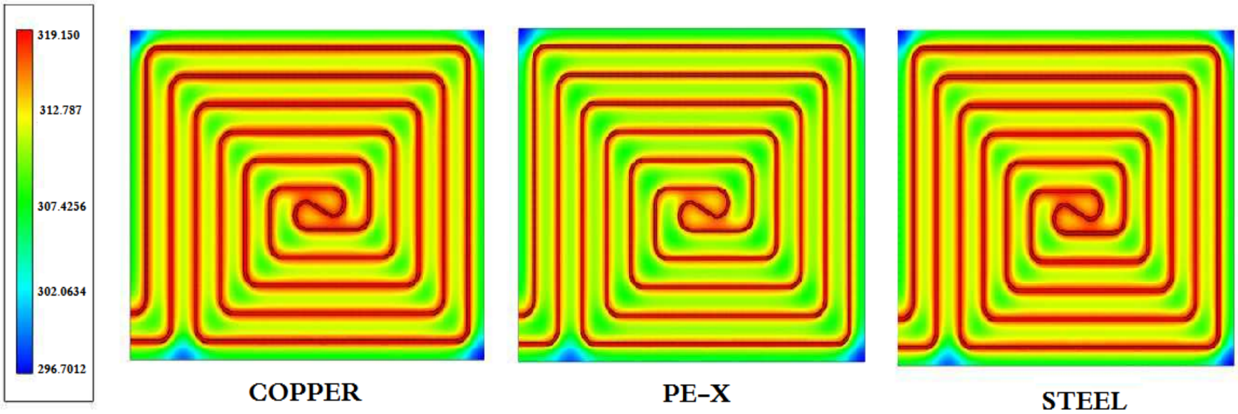


Figure 12. Profil surface temperature for the three pipe materials

more influence on the supply water temperature as well as the energetic performance. The results show that the pipe spacing, pipe materials, screed layer, thermal resistance of floor covering, and the ambient temperature have a large impact on the supply water temperature and heat flux released of the floor. Whereas the thickness of the screed layer and the diameter of the pipe have virtually no effect on the floor surface temperature and the heat flux emitted by the system. Due to the significant impact of the floor covering on the thermal efficiency of the underfloor heating elements, it is preferable to use materials with small thermal resistance and should not exceed R = 0.15 m^2. K / W. It is proposed that the pipe diameter be approximately 20 mm because if the diameter is large, there will be a negative impact on the structural behaviors of the whole system. By comparing a pipe spacing of 15mm and 30mm, we can reach a difference of supply water temperature around 7,4°C. As well as greater the spacing of the pipes, the shape of the heating pipe will be clearer, which generates less floor temperature homogeneity.
The thermal properties of the pipes also have a significant impact on the heating system efficiency. From the simulation result, PE-X is preferred because it presents advantages such as being resistant to corrosion and scaling, low cost, no welding long lengths without connection. Because there is an inevitable relationship between the heat flux released of the heating system and the water supply temperature, this research will enable to choice between different designs characteristics of the floor by using the interpolation method of the graphics values. In addition, it can help the designers by applying the calculation and simulation methodology in choosing the appropriate sizes and materials of the underfloor heating system that ensure adequate heat flux to meet heating needs.

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