THERMAL MODELLING OF SPENT NUCLEAR FUEL POOL STORAGE DURING LOSS OF EXTERNAL COOLING SYSTEM ACCIDENT

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Spent nuclear fuel (SNF) is nuclear fuel that is no longer useful in sustaining a nuclear reaction in the nuclear reactor but still generates heat in term of decay heat, which is of concern for their disposal and transportation. For safety, it needs to be cooled adequately in spent fuel pool (SFP) to a safer level. At present, all SFP are equipped with an external cooling system to ensure the temperature and water level inside the SFP at a safe level. During the loss of an external cooling system accident, the SFP is fully dependent on the natural convection process to cool the SNF. It is important to predict and evaluate the SFP temperature and water level during this accident. Therefore, in this study, a computational model of SFP was developed in order to predict the thermal behaviour of the SFP, focusing on the SFP temperature and water level during the loss of an external cooling system accident. The computational model is based on a three-dimensional (3D) two-phases thermal fluid behaviour computed using the computational fluid dynamic software, Ansys Fluent 18.0. In order to validate the computational model, a small-scale SFP physical model with the ratio of 1 : 30 from the actual size of SFP was developed. Based on the validation process, the developed computational models were deemed applicable to predict the SFP water temperature and water level during the accident. From the computed results, it shows that for 10 MW decay heat, it took 20 hours for the water temperature to achieve the saturation condition and another 102 hours for the water level to decrease on the top part of the SNF. The computational model was further used to investigate the effect of SNF decay heat value and axial temperature distribution on the thermal behaviour of the SFP without an external cooling system. Computations for three different SNF decay heat values (5 MW, 1 MW and 0.1 MW) and three patterns of axial temperature distributions were carried out. The results show that SNF decay heat value affected the increase rate of SFP water temperature and the maximum SNF surface temperature. The result also shows that the effect of SNF axial temperature distribution was larger on the SFP water temperature distribution and its cooling capability. It can be concluded that both the decay heat value and SNF axial temperature distribution have significant effects on the SFP thermal behaviour; therefore, it should be considered in any SFP thermal analysis.

ABSTRAK

Bahan api nuklear terpakai (SNF) merupakan bahan api nuklear yang tidak lagi berguna dalam menampung tindak balas nuklear di dalam reaktor nuklear tetapi masih menghasilkan haba dalam bentuk haba reput yang menjadi kebimbangan semasa pelupusan dan pengangkutan bahan tersebut. Untuk keselamatan, ia perlu disejukkan secukupnya hingga ke tahap yang lebih selamat di dalam kolam bahan api terpakai (SFP). Pada masa ini, semua SFP dilengkapkan dengan sistem penyejukkan luaran untuk memastikan suhu dan tahap air di dalam SFP pada tahap yang selamat. Semasa kemalangan kehilangan sistem penyejukkan luaran, SFP bergantung sepenuhnya kepada proses perolakan semula jadi untuk menyejukkan SNF. Adalah penting untuk meramal dan menilai suhu dan tahap air SFP semasa kemalangan ini. Oleh itu, dalam kajian ini, sebuah model pengiraan SFP telah dibina bagi meramal perlakuan terma SFP dengan memberi tumpuan kepada suhu dan tahap air SFP semasa kemalangan kehilangan sistem penyejukkan luaran. Model pengiraan ini berdasarkan kepada perlakuan bendalir terma dua fasa tiga dimensi (3D) yang dihitung menggunakan perisian pengiraan bendalir dinamik, Ansys Fluent 18.0. Bagi mengesahkan model pengiraan ini, sebuah model fizikal SFP berskala kecil dengan nisbah 1 : 30 daripada saiz sebenar SFP telah dibina. Berdasarkan proses pengesahan, model pengiraan yang dibina dianggap boleh digunakan untuk meramal suhu air dan tahap air SFP semasa kemalangan. Keputusan dari pengiraan menunjukkan bagi haba reput 10 MW, suhu air mengambil masa selama 20 jam untuk mencapai keadaan penepuan, dan 102 jam lagi untuk tahap air berkurang kepada bahagian atas SNF. Model pengiraan kemudiannya digunakan untuk menyiasat kesan nilai haba reput dan agihan suhu paksi SNF terhadap perlakuan terma SFP tanpa sistem penyejukkan luaran. Pengiraan tiga nilai haba reput yang berbeza (5 MW, 1 MW dan 0.1 MW) dan tiga corak agihan suhu paksi SNF telah dijalankan. Keputusan menunjukkan bahawa nilai haba reput SNF mempengaruhi kadar peningkatan suhu air SFP dan suhu maksimum permukaan SNF. Keputusan turut menunjukkan bahawa kesan agihan suhu paksi SNF adalah ketara pada agihan suhu air SFP dan keupayaan penyejukkannya. Kesimpulannya, kesan kedua-dua nilai haba reput dan agihan suhu paksi SNF terhadap perlakuan terma SFP adalah signifikan, oleh itu, ia harus dipertimbangkan dalam setiap analisis terma SFP.

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LIST OF ABBREVIATIONS

ABWR	-	Advanced Boiling Water Reactor
AC	-	Alternate Current
AMG	-	Algebraic Multigrid
BWR	-	Boiling Water Reactor
CFD	-	Computational Fluid Dynamic
DC	-	Direct Current
DNS	-	Direct Numerical Solution
DOM	-	Discrete Ordinate Model
FVM	-	Finite Volume Method
GAMBIT	-	Geometry and Mesh Building Intelligent
GOTHIC	-	Generation of the Thermal Hydraulic Information for Containment
Gr	-	Grashof Number
IAEA	-	International Atomic Energy Agency
ICEM	-	Integrated Computer Engineering and Manufacturing
LWR	-	Light Water Reactor
MAAP5	-	Modular Analysis Program
MOX	-	Mixed Oxide Fuel
NEI	-	Nuclear Energy Institute
NPP	-	Nuclear Power Plant
OpenFOAM	-	Open-Source Field Operation and Manipulation
PDE	-	Partial Differential Equation
PISO	-	Pressure-Implicit with the Splitting of Operators
PRESTO	-	Pressure Staggering Option
PRHR HX	-	Passive Residual Heat Removal Exchanger
PWR	-	Pressurized Water Reactor
QUICK	-	Quadratic Upstream Interpolation for Convective Kinematics
RANS	-	Reynold Average Navier-Stoke
RNG	-	Reynold Normalisation Group
RPI	-	Rensselaer Polytechnic Institute
SFP	-	Spent Fuel Pool

Sh	-	Sherwood Number
SIMPLE	-	Semi-Implicit Pressure Linked Equation
SNF	-	Spent Nuclear Fuel
TRIGA	-	Training, Research, Isotopes, and General Atomic
UDF	-	User Defined Function
V-SA	-	Various Spalart Allmaras
3D	-	Three-Dimensional

LIST OF SYMBOLS

A	-	Area
a	-	Volume fraction
Cp	-	Specific heat capacity
D	-	Mass diffusion coefficient
d	-	Diameter
f	-	Frequency
G	-	Gravitational acceleration
H	-	Height
h	-	Mass transfer coefficient
h_{fg}	-	Latent heat of evaporation
J	-	Diffusion flux
k	-	Turbulent conductivity
l, L	-	Length
M	-	Mass
P	-	Pressure
Pu239	-	Plutonium-239
$Q.q$	-	Heat transfer
R	-	Residual
S	-	Source
T	-	Temperature
t	-	Time
U233	-	Uranium-233
U235	-	Uranium-235
V	-	Volume
W	-	Width
v	-	Kinematic viscosity
φ	-	Scalar variable
∇	-	Gradient
ρ	-	Density

λ	-	Thermal Conductivity
υ, U	-	Velocity
$\bar{\bar{\tau}}$	-	Stress tensor
$\vec{F}$	-	External body force
γ, c	-	Mass fraction
$\dot{m}$	-	Mass flow rate
ε	-	Epsilon
τ	-	Relaxation time
β	-	Thermal expansion coefficient
Γ	-	Diffusion coefficient

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CHAPTER 1

INTRODUCTION

The objective of this Chapter is to provides an overview of this research. The first part of this Chapter introduced the readers to the background of this research and follows with the problem statement. The second part of this Chapter introduced the readers to the aims of this research to solve the problem. The last part of this Chapter discussed on the scopes and the significances of this research.

1.1 Background of the Research

Spent nuclear fuel pool or usually called spent fuel pool (SFP) is the storage pool which store the spent nuclear fuel (SNF) since the SNF still generates the amount of heat and radiation due to decaying fission product. The SNF usually stored underwater, which provides both cooling and shielding against radiation (IAEA, 1992). Therefore, an adequate level of heat removal of the storage pool must be determined to ensure that temperature limits are not exceeded in any condition.

Generally, external cooling and air ventilation systems are installed in the SFP to ensure safe temperature levels in the water. Both of these systems are powered by electrical supplies (AC and DC). Without electrical supplies, both cooling systems will stop working thus increasing the temperature inside the SFP and decreasing the water level in the SFP due to vaporization process.

The tragedy in Fukushima Daiichi in 2011 due to the loss of external cooling system had resulted in an increase in the awareness of ensuring safe temperature in the SFP water at any condition. During this accident, natural convection circulation process plays an important role in removing the decay heat from the SNF. Even the heat transfer from this process might not be able to ensure enough heat removal to keep the temperature in the SFP at the safe level, but the process might be able to reduce the rate of water temperature increase during this accident.

Appropriate analysis should be taken by considering the thermal behaviour of the SFP during the loss of external cooling system accident. Thus, this research aims to model the thermal behaviour of the SFP during the loss of external cooling system accident and investigate some of the effects that influence the thermal behaviour of the SFP during this accident. This research was also investigating the possibility to improve the self-cooling capability of the SFP based on these effects.

1.2 Problem Statement

It is important to continuously monitor the SFP parameters at any conditions. The SFP water temperature and the water level are among the most important parameters that indicate the SFP condition. The water temperature and water level in the SFP is maintained by an external cooling system. During the loss of external cooling system accidents, the heat transfer from the SNF to the entire SFP is dependent on the natural convection process. This natural convection process acted as the internal passive cooling system in the SFP which determines the thermal behaviour of the SFP during the loss of an external cooling accident. Appropriate procedures should be taken to predict the SFP thermal behaviour during this accident.

One of the most popular methods to predict the thermal behaviour of the SFP is by developing the SFP thermal model using a computational approach. There are several research conducted to predict the thermal behaviour of the SFP during the loss of external cooling system accidents by developing the computational model but most of these models are proprietary and not available to the public. Some of the models previously developed were too complicated to be used and the method used is still in doubt. Besides, most of the developed model was also does not consider or take for granted the ability and the effect of some important parameters such as natural convection process inside the SFP (Gauntt et al, 2012). Hence, there is a need to establish a method to develop SFP thermal model during the loss of external cooling accident for further investigation. Therefore, a computational model of the SFP to predict the thermal behaviour of the SFP during the loss of external cooling accident was developed.

The natural convection process is the one of the important factors that determine the thermal behaviour of the SFP during the absences of the external cooling system. The rate of natural convection process depends on the temperature gradient in the SFP. To improve the rate of the natural convection process in the SFP, the factor affecting the temperature distribution in the SFP should be well understood. Since the temperature distribution in the SFP occurs due to the heat generated from the SNF, the SNF itself should be investigated as one of the factors affecting the temperature distribution in the SFP. One of the parameters related to the SNF which has not yet investigated is the SNF axial temperature distribution. All the previous research conducted assumes the SNF axial temperature distribution is uniform along with the SNF and the effect of this parameter on the SFP temperature distribution were neglected. It is important to know the effect of this parameter on the SFP temperature distribution thus can improve the natural cooling capability of the SFP. Therefore, in this research, the effects of the SNF axial temperature distribution on the temperature distribution in the SFP were investigated.

There were also several previous research conducted to investigate the passive cooling capability of the SFP during the loss of the external cooling system accident. Most of the results show that the heat generated from the SNF is not transferred and distributed efficiently to the entire part of the SFP. Some improvement should be made to the current configuration of the SNF in the SFP, so it can transfer and distribute the heat efficiently to the entire SFP. Therefore, based on the parameters investigated, this research has determined the improvement factors or optimum SNF configuration which can improve the rate of heat transfer in the SFP during the loss of external cooling system accident.

1.3 Objectives of the Research

Based on the preceding challenge and issues, this research is centred on the following objectives.

1. To model the thermal behaviour of the spent fuel pool during the loss of external cooling system accident.

2. To investigate the effect of spent nuclear fuel decay heat and axial temperature distribution on the thermal behaviour of the spent fuel pool during the loss of external cooling system accident.

3. To determine improvement factors which can improve the passive cooling capability of the spent fuel pool during the loss of external cooling system accident.

1.4 Scope of the Research

In this research, a computational approach was used to develop the thermal model of SFP during the loss of external cooling system accident without considering others SFP parameters such as SFP criticality. The computation also does not consider any others accident such as loss of flow accident. The computations were computed by using computational fluid dynamic (CFD) software, Ansys Fluent 18.0. The design of the SFP used in this research is based on the conceptual design. In term of heat source, uniform SNF decay heat were used for all SNF in the SFP. Any change on the value of decay heat due to some factors such as the decay of the radionuclides and SNF loading time were neglected.

Both single-phase and two-phase computation models based on conduction and convection heat transfer process were developed. Heat transferred due to radiation were not considered. The computation model then was used to investigate the effect of SNF axial temperature distribution on the temperature distribution in the SFP. Three different patterns of SNF temperature distribution were investigated. Other parameters and factors which have been proven or has not been prove affecting the temperature distribution in the SFP such as SNF assembly's arrangement, air movement conditions, SNF radial temperature distribution, and auxiliary cooling system were not investigated and were keep constant throughout the research.

1.5 Significance of the Research

In this research, the data and the results obtained provide meaningful information to assist the designer of SFP storage especially in term of SFP thermal analysis. This research suggested the suitable methods and steps in developing the SFP computational thermal model. The developed computational model can be used to predict the thermal behaviour of the SFP during the loss of external cooling system accident. The developed two-phase model also can be used to predict the SFP future condition such as the SFP water level. Appropriate actions can be taken based on this prediction. The developed model can be also applied to all types of SFP and other heat-related problems.

This research also comes out with suggested SNF configurations in the SFP which can improve the heat transfer process in the SFP thus improving the natural cooling capability of the SFP. This improvement increased the SFP water boil-up time during accident thus increasing the safety level of the SFP. This improvement will also reduce the operating cost of the SFP since the natural cooling capability of the SFP were increase. This model could also be a reference to assist the designer in designing a long-term passive cooling system of the SFP or other related heat transfer system. Completely passively cooling spent fuel pool is one of the key technologies for the long-term passive cooling system (Ye et al, 2013).

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Appendix A Sample analytical calculations for small-scale experimental model

The heat balance equation during heating and boiling process:

During heating process (T<100°C)

$Q_D = Q_H + Q_E + Q_C$

$Cp_w M_w \left(\frac{dT_w}{dt}\right) = Q_D\text{-}Q_E\text{-}Q_C$

All the calculation parameters during heating process were based on average temperature which is 60 °C.

1. Heat loss at the concrete wall due to conduction process:

Calculation parameters:

$Q_D = 3600\text{W}, \lambda_c = 0.6\frac{\text{W}}{\text{mK}}, d_w = 0.07\text{m}, A = 1.3924\text{m}^2, Cp_w = 4.187\frac{\text{kJ}}{\text{kgK}},$

$M_w = 60.75\text{kg}$

Calculation:

$$Q_C(T) = \frac{\lambda_c(T_{ci}\text{-}T_{co})}{d_w}A$$

$$= 0.6\left(\frac{\text{W}}{\text{mK}}\right) \times \frac{20}{0.07}\left(\frac{\text{K}}{\text{m}}\right) \times 1.3924(\text{m}^2)$$

$$= 238.7\text{ W}$$

2. Heat loss at the water surface due to evaporation process:

Calculation parameters:

$h_{fg} = 2260\frac{\text{kJ}}{\text{kg}}, A = 0.135\text{m}^2, \rho_a = 1.22\frac{\text{kg}}{\text{m}^3}, \frac{\rho_0\text{-}\rho_\infty}{\rho_\infty} = 0.204, l = 0.5\text{m},$

$P = 101.325\text{kPa}, P_{S0} = 10\text{kPa}, v = 0.0475 \times 10^{-5}\frac{\text{m}^2}{\text{s}}, D = 2.82 \times 10^{-5}\frac{\text{m}^2}{\text{s}}$

$$Gr = g\left|\frac{\rho_o\text{-}\rho_\infty}{\rho_\infty}\right| = 9.81|0.204|\frac{0.5^3}{(0.0475\times 10^{-5})^2} = 1.11\times 10^{12}$$

$$c = \frac{v}{D} = \frac{0.0475\times 10^{-5}}{2.82\times 10^{-5}} = 0.0168$$

$$Sh = 1.65\times 0.0185Gr^{0.4}Sc^{0.4} = 391$$

$$h_D = \frac{ShD}{l} = \frac{391(2.82\times 10^{-5})}{0.5} = 0.02$$

$$Q_E = h_D\rho_a\left(\frac{0.622P_{S0}}{P}\right)h_{fg}A$$

$$= 0.02\left(\frac{m}{s}\right)\times 1.22\left(\frac{kg}{m^3}\right)\times\left(\frac{0.622\times 10kPa}{101.325kPa}\right)\times 2260\ \left(\frac{kJ}{kg}\right)\times 0.135(m^2)$$

$$= 0.45\ kW$$

Therefore, the time taken for the temperature of the water reach 100 °C:

$$Cp_wM_w\left(\frac{dT_w}{dt}\right) = 3.6\ kW\text{-}0.238\ kW\text{-}0.45\ kW$$

$$4.187\times 60.75\times\left(\frac{dT_w}{dt}\right) = 2.92\ kW$$

$$\frac{dT_w}{dt} = 0.0115$$

$$dt = 6097\ s = 1\ hours\ 40\ minutes$$

During boiling process (100°C):

$$Q_D = Q_B + Q_E + Q_C$$

$$\left(\frac{dM_w}{dt}\right)h_{fg} = \text{-}(Q_D\text{-}Q_C\text{-}Q_E)$$

All the calculation parameters during heating process were based on saturation temperature, 100 °C.

1. Heat loss at the concrete wall due to conduction process:

Calculation parameters:

$Q_D = 3600W, \lambda_c = 0.6\frac{W}{mK}, d_w = 0.07m, A = 1.3924m^2, Cp_w = 4.187\frac{kJ}{kgK},$

$M_w = 60.75kg$

Calculation:

$$Q_C(T) = \frac{\lambda_c(T_{ci}\text{-}T_{co})}{d_w}A$$

$$= 0.6\left(\frac{W}{mK}\right) \times \frac{50}{0.07}\left(\frac{K}{m}\right) \times 1.3924(m^2)$$

$$= 0.546kW$$

2. Heat loss at the water surface due to evaporation process:

Calculation parameters:

$h_{fg} = 2260\frac{kJ}{kg}, A = 0.135m^2, \rho_a = 1.22\frac{kg}{m^3}, \frac{\rho_0\text{-}\rho_\infty}{\rho_\infty} = 0.204 , l = 0.5m,$

$P = 101.325kPa, P_{S0} = 15kPa, v = 0.0294 \times 10^{-5}\frac{m^2}{s}, D = 3.81 \times 10^{-5}\frac{m^2}{s}$

Calculation:

$$Gr = g\left|\frac{\rho_0\text{-}\rho_\infty}{\rho_\infty}\right|\frac{l^3}{v^2} = 9.81|0.204|\frac{0.5^3}{(0.0294 \times 10^{-5})^2} = 2.9 \times 10^{12}$$

$$Sc = \frac{v}{D} = \frac{0.0294 \times 10^{-5}}{3.81 \times 10^{-5}} = 0.00772$$

$$Sh = 1.65 \times 0.0185Gr^{0.4}Sc^{0.4} = 421$$

$$h_D = \frac{ShD}{l} = \frac{967(3.81 \times 10^{-5})}{0.5} = 0.03$$

$$Q_E = h_D\rho_a\left(\frac{0.622P_{S0}}{P}\right)h_{fg}A$$

$$= 0.03\left(\frac{m}{s}\right) \times 1.22\left(\frac{kg}{m^3}\right) \times \left(\frac{0.622 \times 15kPa}{101.325kPa}\right) \times 2260\left(\frac{kJ}{kg}\right) \times 0.135(m^2) = 1\ kW$$

The remaining heat were assumed used to change the phase of water:

$$Q_D = Q_B + Q_E + Q_C$$

$$\left(\frac{dM_w}{dt}\right) 2260 = \text{-(3.6kW-0.546 kW-1 kW)}$$

$$\left(\frac{dM_w}{dt}\right) = 0.00092$$

The total mass of water loss when the water level reached the top part of heater:

$$H_w = \frac{M_w}{\rho_w A_{ws}}$$

$$0.33(m) = \frac{M_w}{1000\left(\frac{kg}{m^3}\right) \times 0.135(m^2)}$$

$$M_w(kg) = 44.55$$

$$dM_w(kg) = 44.55 \text{ kg}$$

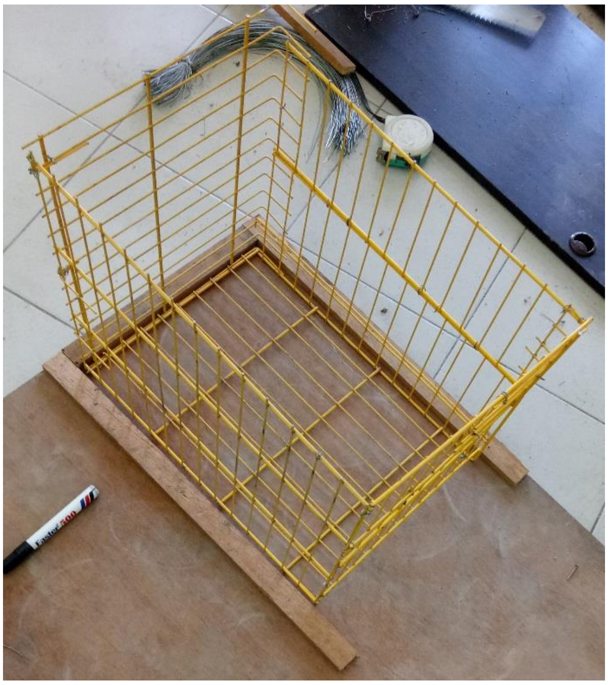
If the total mass of the water loss from the model is 44.5(kg), the time taken for the water level drop to the top surface of heater is:

$$\left(\frac{44.55(kg)}{dt}\right) = 0.00092$$

$$dt = 48000 \text{ s} \approx 13 \text{ hours}$$

Appendix B Construction of small-scale experimental model

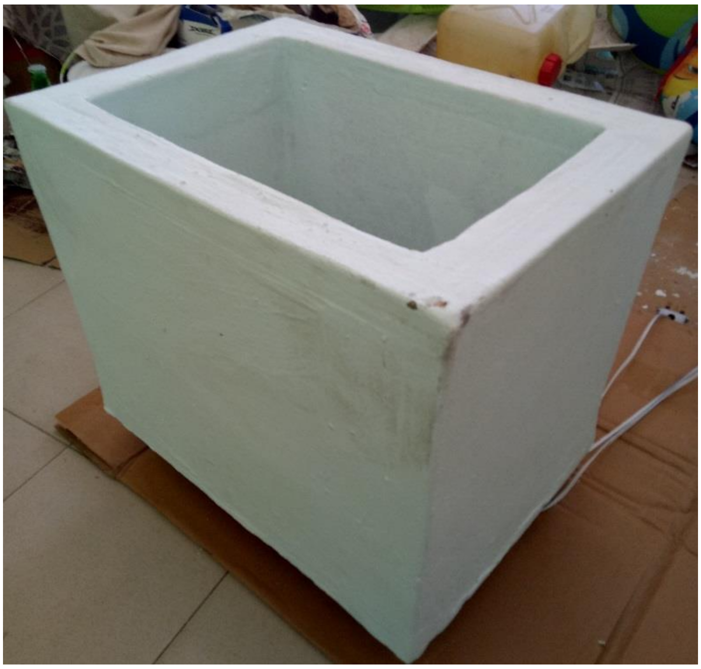
1. Setting up the steel frame and dimension of the small-scale experimental model



2. Construction of the model

3. Setting up the electrical component

4. Coating the concrete with waterproof paint



5. Waterproof testing