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UNIVERSITI TEKNOLOGI PETRONAS

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by

JOKO WALUYO

The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance this thesis for the fulfillment of the requirements for the degree stated.

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SIMULATION MODELS FOR SINGLE AND TWO-STAGE CHARGING OF STRATIFIED THERMAL ENERGY STORAGE

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JOKO WALUYO

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DECLARATION OF THESIS

Title of thesis	SIMULATION MODELS FOR SINGLE AND TWO-STAGE CHARGING OF STRATIFIED THERMAL ENERGY STORAGE

I JOKO WALUYO

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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ABSTRACT

The current practice of charging thermal energy storage (TES) tank is by using electric chillers. One of the main reasons is that the temperature limitation of the absorption chillers which might lead to freezing the refrigerant. This was the reason the absorption chillers at co-generated district cooling plants are not being utilized to charge the TES tank. This research focuses on the development of models incorporating absorption chiller to complement electric chiller to charge a stratified TES tank of a co-generated district cooling plant. The models were developed using two approaches, namely temperature distribution analysis approach and heat transfer approach. For the case of temperature distribution analysis, a function was selected to represent its profile. Functional relationship of the temperature distribution was used to formulate thermocline thickness, thermocline limit points, temperature transition point and limit capacity criteria. Using temperature distribution function, simulation model was then developed based on an open charging system. For the heat transfer approach, the models were developed as a close system by integrating the TES tank and chiller equipments. For the TES tank, one-dimensional flow conductive-convection analysis was used, while the chillers utilized energy balance analysis. For both approaches two types of models, namely single stage and two-stage models were developed. The single stage model is limited to using electric chiller to charge the TES tank. While the two-stage models incorporate both the absorption and electric chillers with the absorption and the electric chillers function in sequence to charge the TES tank. Validation was performed on the single stage charging for both approaches. Results show similarities of temperature distribution values of R^2 greater than 0.98 and parameters deviation lower than 6%. From statistical test acceptance analysis for the single stage model, *t*-computed has highest value of 0.035, which is lower than critical value of 2.145 from the *t*-distribution table. This indicates that both models were statistically acceptable. Comparisons of the single and two-stage models between the two approaches were also performed using simulation case studies.

Results imply that the models are capable of predicting charging characteristic, with deviations lower than 4% for the charging durations and below 2% for the cumulative cooling capacity. Findings from simulations of the two-stage models indicate that the absorption chillers could be used to charge the TES in combination with electric chillers.

ABSTRAK

Amalan semasa untuk mengisi tangki penyimpan tenaga thermal (TES) adalah dengan menggunakan chiller elektrik. Salah satu alasan utama kerana sekatan suhu chiller yang menyebabkan pembekuan refrigeran. Ini menjadi alasan chiller penyerapan di distrik pendingin tidak dimanfaatkan untuk mengisi tangki TES. Penyelidikan ini berfokus pada pembangunan model dengan chiller penyerapan untuk melengkapkan chiller elektrik untuk mengisi tangki TES stratifikasi di distrik pendingin. Model dikembangkan dengan dua jenis pendekatan, iaitu analisis pengedaran suhu dan pengedaran panas. Untuk analisis pengedaran suhu, fungsi yang dipilih untuk mewakili profil hubungan fungsional pengedaran suhu digunakan untuk merumuskan ketebalan termoklin, titik batas termoklin, titik peralihan suhu dan kriteria batas kapasiti. Menggunakan fungsi pengedaran suhu, model simulasi kemudian dikembangkan berdasarkan sistem pengisian terbuka. Untuk pendekatan pengedaran panas, model dikembangkan sebagai sistem tertutup, dengan mengintegrasikan tangki TES dan peralatan chiller. Untuk tangki TES, digunakan aliran satu-dimensi konduktif-konveksi analisis, sedangkan untuk chiller digunakan analisis tenaga keseimbangan. Untuk kedua-dua pendekatan dibangunkan dua jenis model, iaitu untuk tahap tunggal dan dua tahap. Model tahap tunggal terhad menggunakan chiller elektrik untuk mengisi tangki TES. Sementara model dua tahap menggabungkan baik chiller penyerapan dan elektrik, dengan pengisisian chiller penyerapan dan elektrik secara berturutan. Validasi dilakukan ke atas model tahap tunggal untuk kedua-dua pendekatan tersebut. Keputusan kajian menunjukkan kesamaan nilai pengedaran suhu, R^2 lebih besar dari 0,98 dan deviasi parameter lebih rendah daripada 6%. Dari analisa statistik penerimaan, t-dikira mempunyai nilai tertinggi 0.035, yang lebih rendah dari nilai kritikal 2,145 dari t-tabel. Hal ini menunjukkan bahawa kedua-dua model secara statistik boleh diterima. Perbandingan kedua-dua model tahap tunggal dan dua tahap antara dua pendekatan juga dilakukan pada berbagai kes simulasi. Keputusan menunjukkan bahawa model mampu memprediksi karakter pengisian dengan penyimpangan yang lebih rendah daripada 4% untuk jangka masa pengisian dan di bawah 2% untuk kapasiti pendinginan kumulatif. Penemuan dari simulasi ke dua

model dua tahap menunjukkan bahawa chiller penyerapan boleh digunakan untuk mengisi tangki TES digabungkan dengan chiller elektrik.

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NOMENCLATURE

A	cross sectional area of the tank (m^2)
AMIX	stability of conduction equation, AMIX = $\alpha.\varepsilon_{eff}\ (\Delta t/\Delta x^2) \leq 0.5$
B	bottom limit point of thermocline
C	position of midpoint of thermocline
C_E	cool water depth at empty capacity (m)
C_F	cool water depth at full capacity (m)
C_{FR}	cool water depth at temperature transition point (m)
C_{FT}	cool water depth at full capacity of the first stage charging (m)
C_p	specific heat (J/kg.^{o}C)
D	diameter of tank (m)
f	number of degree of freedom
FLOW	stability of convection equation, FLOW = $v.\Delta t/\Delta x \leq 1$
H	effective water depth of the tank (m)
k	thermal conductivity (W/m.^{o}C)
L	segmental element of tank
ln	log natural number
M_n	mass of water at each slab of the tank (kg)
$\dot{m}_C$	mass flow rate (kg/sec)
N	amount of slabs number in TES tank
n	number of temperature data, number of slab
N_L	lower nozzle elevation (m)
N_T	upper nozzle elevation (m)
P	tank perimeter (m)
PL	partial load of charging
$Qabs$	heat inputted to absorber of absorption chiller (kW)
Q_C	design cooling capacity the chillers (kW)
$Q_{C,des}$	design cooling capacity the chillers (kW)
$Qcond$	heat rejected from condenser (kW)
Q_{cum}	cumulative cooling capacity (kWh)
Qev	heat inputted to evaporator (kW)
$Qgen$	heat supplied to generator (kW)
S	slope gradient of thermocline profile
T	water temperature (^{o}C)
t	time (minutes)
T_Θ	cut-off temperature (^{o}C)
T_a	ambient temperature (^{o}C)
T_c	average cool water temperature (^{o}C)
t_{CF}	charging duration for full capacity (minutes)
t_{CFR}	charging duration to achieve transition temperature (minutes)
t_{CFT}	charging duration for full capacity at first stage charging (minutes)

T_{ev}	evaporator temperature (^oC)
T_h	average of warm water temperature (^oC)
T_{inC}	inlet chilled water temperature (^oC)
$T_{inC,des}$	designed inlet chiller temperature (^oC)
T_{inTES}	inlet charging temperature (^oC)
T_{LC}	temperature at water volume which is influenced by mixing (^oC)
T_{mix}	mixing temperature (^oC)
T_n	water temperature at each slab (^oC).
T_{outC}	outlet chilled water temperature (^oC)
$T_{outC,des}$	designed oulet chiller temperature (^oC)
T_{outTES}	outlet charging temperature (^oC)
T_r	limit temperature (^oC)
T_r	reference temperature (^oC)
T_x^t	instantaneous temperature at elevation *x* and time interval *t* (^oC)
U	upper limit point of thermocline
UA	overall heat transfer coefficient times area ($kW/^oC$)
v	vertical velocity in the tank (m/sec)
V_{LC}	water volume influenced by mixing (m^3)
$\dot{V}_C$	charging flow rate (m^3/hr)
$\dot{V}_{C1}$	charging flow rate of the first stage charging(m^3/hr)
$\dot{V}_{C2}$	charging flow rate of the second stage charging (m^3/hr)
W_{TC}	thickness of thermocline
x	tank elevation, elevation of mid point of the slab (m)
X	dimensionless elevation of the tank, $X = x.N/H$

Greek Symbols

Θ	dimensionless cut-off ratio
α	thermal diffusivity (m^2/sec)
β	significance level
ε_{ef}	effective diffusivity factor
ρ	density (kg/m^3)
ΔC	increasing of cool water depth during charging (m), $\Delta C = \dot{V}_C / A$
Δt	time interval
ΔT_1	temperature losses at outlet connection of the tank (^oC)
ΔT_2	temperature losses at inlet connection of the tank (^oC)
Δx	segmental element of the tank (m)

Statistics Symbols

H_a	alternative hypothesis	, H_a: $y_i^1 - y_i^2 \neq 0$
H_o	null hypothesis	, H_o: $y_i^1 - y_i^2 = 0$

t comp	ratio of the temp. data value difference and standard deviation.
t critical	table t distribution refer to $t_{(f,\beta/2)}$
σ_1, σ_2	standard deviation of temp. distribution observed data and model
$\bar{y}^1$, $\bar{y}^2$	mean value of temperature distribution observed data and model
y_i^1, y_i^2	values of temperature distribution of the observed data and model

Simulation Cases and Designated Data

A1, B1, D1	: simulation cases of single stage charging in model type (I)
A2, B2, D2	: simulation cases of single stage charging model type (II)
E1, F1, G1	: simulation cases of two-stage charging model type (I) with flow rate variation
E2, F2 G2	: simulation cases of two-stage charging model type (II) with flow rate variation
H1, J1, K1	: simulation cases of two-stage charging in model type (I) with limit temperature variation
H2, J2, K2	: simulation cases of two-stage charging in model type (II) with limit temperature variation
IA, IB, IC	: data sets of temperature distribution at flow rate 393 m^3/hr
IIA, IIB, IIC	: data sets of temperature distribution at flow rate 524 m^3/hr