Modeling and Analyse of a Direct Expansion Geothermal Heat Pump (DX) : part 1 Modeling of Ground Heat Exchanger

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Abstract: Geothermal heat pump technology is actually one of the most interesting processes to provide heat and cold to a building. In this study, a model of the ground exchanger of a direct expansion geothermal heat pump (DX) is going to be presented in 1 dimension. The model represents the phase change of the refrigerant, here Chlorodifluoromethane R22, with governing continuity, momentum and energy equations and with heat exchange between pipe and grout. A comparison of the temperature of the pipe with an experience is presented. This result validated our model.

Keywords: Phase Change, Heat pump, Direct Expansion Geothermal Heat Pump

1. Introduction

Geothermal heat pump technology is actually one of the most interesting processes to provide heat and cold to building. There are two design uses in the industry, geothermal heat pump using a secondary ground loop and Direct Expansion (DX) ground source heat pump. Both operate on the simple vapor compressor refrigeration cycle. The main difference is that on the DX geothermal heat pump, figure 1, the ground heat exchanger is part of the refrigeration cycle [1]. So, the energetic and operational performances of the system are directly related to the working fluid behavior, the refrigerant, in relation with the ground heat transfer.

The literature review revealed a lack of scientific research and publication direct expansion geothermal heat pump systems [1, 2]. So in terms of modeling and experimental results, the information available does not have sufficient scientific knowledge with respect to this technology. Therefore, the proposed modeling and analysis of this heat pump DX aims to fill this gap.

Modeling and analysis of a geothermal heat pump direct expansion begins with modeling these different components: Ground heat exchanger, compressor, thermostatic expansion valve, reversing valve, pipe, water-refrigerant exchanger, etc. and the coupling of these components to make a closed loop corresponding to the heat pump.

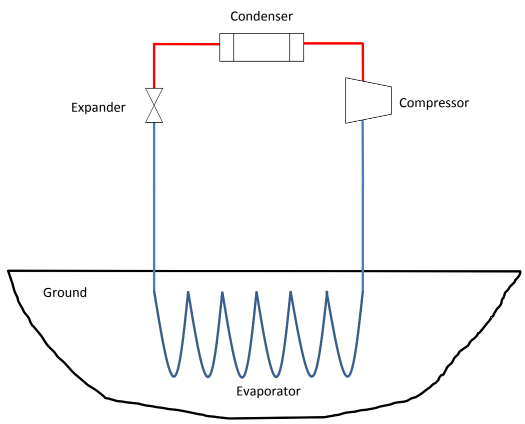

Figure 1. Direct Expansion Geothermal Heat Pump (DX)

This study is in two part, in the first part, the model of ground heat exchanger is presented and in part 2 it's the model of the second exchanger (with water in that case).

In this study, a model of the ground exchanger working like an evaporator is going to be presented in 1 dimension, see figure 2. The model represents the phase change of the refrigerant, here Chlorodifluoromethane R22, with governing continuity, momentum and energy equations and with heat exchange between pipe and grout. This equation is solved by the use the PDE interface to program the governing equation. To take account the effect of the tube between them, two flows is created, one for the ascending flow and one for the descending flow. The pipe and the grout are modeled with the heat transfer mode of COMSOL.

Nomenclature

A	Intern section of the pipe	(m^2)
Cp	Specific heat	(J/kg.K)
De	Extern diameter of the pipe	(m)
Di	Intern diameter of the pipe	(m)
f	friction factor	
G	Mass velocity	($kg/s.m^2$)
g	Gravitational acceleration	(m/s^2)
H_r	Heat transfer coefficient, between the pipe and the flow	($W/m^2.s$)
Hs	Heat transfer coefficient, between the pipe and the grout	($W/m^2.s$)
H_p	Heat transfer coefficient, between the grout and the ground	($W/m^2.s$)
h	Specific enthalpy	(J/kg)
h_{fg}	Enthalpy of Phase Changes	(J/kg)
k	Thermal conductivity	(W/m.K)
L	Length of the pipe	(m)
$\dot{m}$	Mass flow rate	(kg/s)
P	Pressure	(Pa)
Pr	Prandtl Number	
Re	Reynold Number	
T	Temperature	(K)
x	Quality of Vapor	
z	Depth	(m)

Greek

ρ	Density	(kg/m3)
μ	Dynamic viscosity	(Pa.s)
θ	Angle of the pipe compare to the horizontal	(kg/m3)
σ	Surface tension	(N/m)
υ	Speed of the R22	(m/s)

Subscripts

c	Grout
f	Liquide phase
g	Gaz phase
m	Mixture of liquid and gaz of R22
p	Pipe
s	Ground
i	At the entry of the evaporator

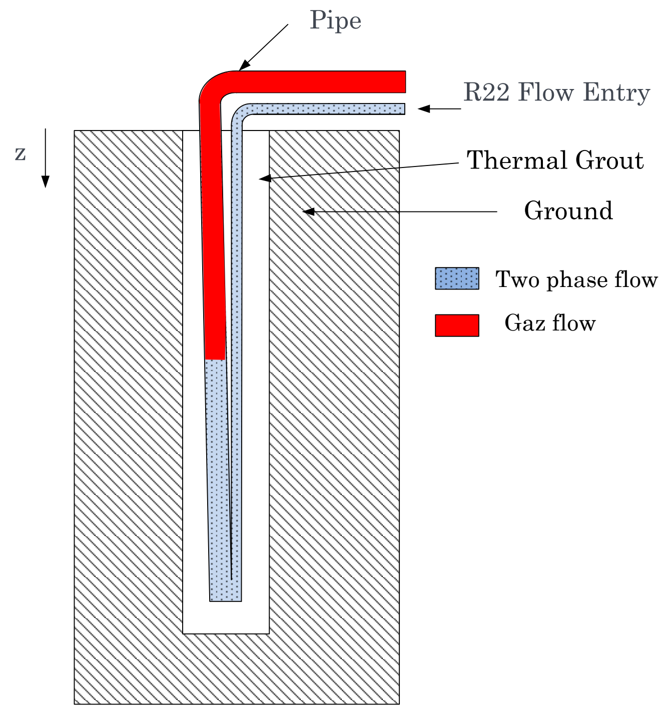

Figure 2. Ground Heat Exchanger

2. Theory

In this study, we need to resolve governing continuity, momentum and energy and heat exchange between the flow and the pipe, and the pipe and the ground.

For the R22, the homogeneous multiphase flow is used [3] equation 1-3:

$$\frac{\partial \rho_m A}{\partial t} + \frac{\partial \dot{m}}{\partial z} = 0 \quad (1)$$

$$\frac{\partial \dot{m}}{\partial t} + \frac{\partial \dot{m} v}{\partial z} + \frac{\partial P_m A}{\partial z} = -\tau \times Pr - \rho \times A \times g \times \sin\theta \quad (2)$$

$$\frac{\partial \rho_m A h_m}{\partial t} + \frac{\partial \dot{m} h_m}{\partial z} = \frac{\partial P_m A}{\partial t} + q_r \quad (3)$$

With

$$q_r = Hr \times Pr \times (T_p - T) \quad (4)$$

$$\tau_w = \frac{f \dot{m} v}{8} \quad (5)$$

In z=0, the condition at the entry of the evaporator for in descending flow:

$$\dot{m} = \dot{m}_i$$

$$P_m = P_i$$

$$h_m = h_i = h_f + h_{fg} \times x_i$$

The same condition is imposed for all z in t=0.

Hr in equation 5 is calculated with Gnielinski [4], equation (6), for one phase flow and Chen [5] correlation for two phase flow (7).

$$H_r = \left(\frac{k_m}{D_i}\right)\left[\frac{\left(\frac{f}{8}\right)(Re-1000)Pr}{1+12.7\left(\frac{f}{8}\right)^{1/2}(Pr^{2/3}-1)}\right] \quad (6)$$

Chen Correlation :

$$H_r = H_{mic} + H_{mac} \quad (7)$$

$$H_{mic} = 0.00122\left[\frac{k_f^{0.79} Cp_f^{0.45} \rho_f^{0.49}}{\sigma^{0.5} \mu_f^{0.29} h_{fg}^{0.24} \rho_g^{0.24}}\right] \times [T_p - T_{sat}(P_m)]^{0.24}[P_{sat}(T_p) - P_m]^{0.75} S \quad (8)$$

$$S = \frac{\left[1-exp\left(-\frac{F(X_{tt})H_f X_0}{k_f}\right)\right]}{\frac{F(X_{tt})H_f X_0}{k_f}} \quad (9)$$

$$X_0 = 0.041\left[\frac{\sigma}{g(\rho_f-\rho_g)}\right]^{0.5} \quad (10)$$

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}\left(\frac{\mu_f}{\mu_g}\right)^{0.1} \quad (11)$$

$$H_f = 0.023\left(\frac{k_f}{D_i}\right) Re_f^{0.8} Pr_f^{0.4} \quad (12)$$

$$Re_f = \frac{G(1-)Di}{\mu_f} \quad (13)$$

$$H_{mac} = H_f F(X_{tt}) Pr_f^{0.296} \quad (14)$$

$$F(X_{tt}) = 1 \text{ if } X_{tt}^{-1} \le 0.1 \quad (15)$$

$$F(X_{tt}) = 2.35\left(0.213 + \frac{1}{X_{tt}}\right)^{0.736} \text{ if } X_{tt}^{-1} > 0.1$$

The pressure drop in case of two phase flow in the tube is calculated with the Müller-Steinhagen and Heck Correlation [6].

For the pressure drop of the bend, in this study the correlation of Domanski [7] is used.

The temperature of the pipe and the grout is solve with the equation (17-18) and (19-20) :

$$\rho_p \times A_p \times Cp_p \times \frac{dT_p}{dt} = -q_r + q_p + k_p \frac{\partial^2 T_p}{\partial z^2} \quad (17)$$

$$q_p = H_p \times P_p \times (T_c - T_p) \quad (18)$$

$$\rho_c \times A_c \times Cp_c \times \frac{dT_c}{dt} = -q_{p1} - q_{p2} + q_s + k_c \frac{\partial^2 T_c}{\partial z^2} \quad (19)$$

$$q_s = H_s \times P_s \times (T_s - T_c) \quad (20)$$

q_{p1} and q_{p2} are respectively the flux of the descending flow pipe and ascending flow pipe to the grout.

For the calculation of Hs and Hp, the model of Lamarche & al is used in this study [8-9].

3. Use of COMSOL

Like say in the introduction, this study is resolve in one dimension, to take account the effect of one pipe to the over one, we solve, figure 3:

- Two PDE modules for the flow, descending flow and ascending flow.
- Two Heat Transfer modules, for the pipe of descending flow and ascending flow.
- A Heat Transfer module for the grout.

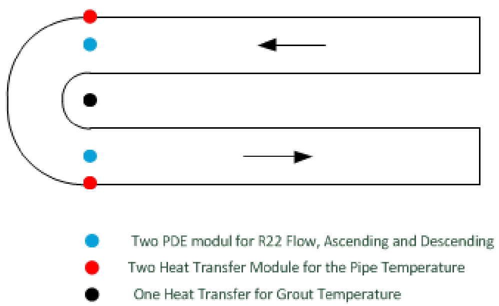

Figure 3. COMSOL Model

The difference between the two flows is the change of sign of the gravity and the pressure drop in the bend.

REFRPROP is used to create a table for the estimation of the property of the mix between Vapor and liquid.

In this preliminary study, the temperature of the ground is constant. In a more detailed study this temperature need to be calculate using the flux of the ground, like in the study of Lamarche [9].

To take account the change of the correlation between one phase flow and two phase flow, the "Flc2hs" function of COMSOL command is use.

4. Comparison between model and experimentation

To validate the model created, a comparison between an experimentation running in our laboratory is presented.

To simplify the problem, the pressure at the entry is the only variable to change in time, the quality and the mass flow rate is fixed, see table 1 and 2.

The experiment allows us to have 4 temperatures of the pipe measurements:

- z=0 of the descending flow
- z=24 m of the descending flow
- z=30 m in the 180° bend.
- z=24m in the ascending flow.

With the temperature at the entry of the descending flow and with the hypothesis that the difference between the temperature of the pipe and the flow is approximated 0.5 K (based on the model and experimentation), the pressure at the entry can be determined by using the sutured pressure with the temperature of the pipe minus 0.5 K. The pressure at the entry is presented at the figure 4.

Table 1: Entry condition of the model

Variables	Values
m_i (kg/s)	0.02
x_i	0.137

Table 2: Parameter of the model

Variables	Values
Di, descending flow (m)	0.0079
Di, ascending flow (m)	0.0110
Ts initial (K)	283
Tpipe at t=0 (K)	283
Le. Descending flow (m)	30
Le. Ascending flow (m)	30
Diameter borehole (m)	0.076
Distance between pipe (m)	0.015

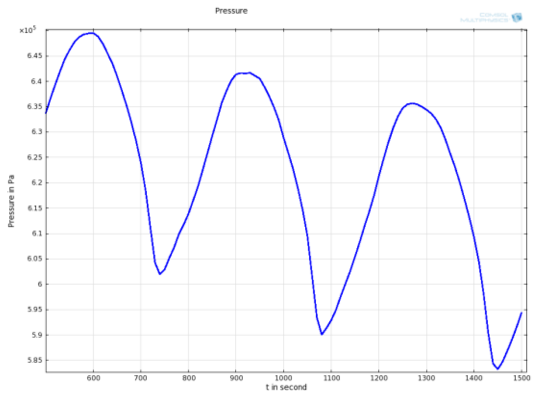

Figure 4. Pressure at the entry of the evaporator

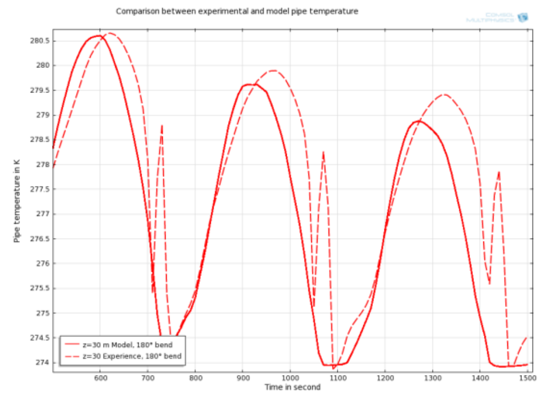

Figure 7. Comparison between temperature of the pipe at z=30 m at the 180° bend

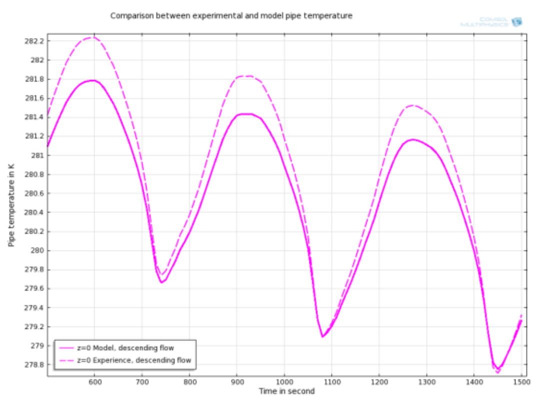

Figure 5. Comparison between temperature of the pipe at z=0 m of the descending flow

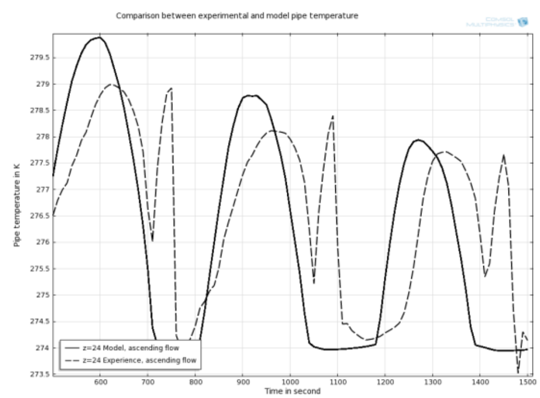

Figure 8. Comparison between temperature of the pipe at z=24 m of the ascending flow

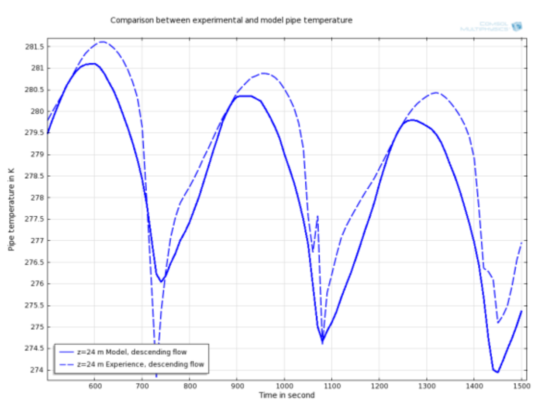

Figure 6. Comparison between temperature of the pipe at z=24 m of the descending flow

The figure 5 show the temperature of the pipe at z=0 meter, at the entry, the difference between the model and the experiment is very small.

The figure 6 is the measured temperature and calculated temperature at z= 24m. The evolution of the temperature is the same and there is a little difference between the temperatures, but it's acceptable.

The figure 7 show the temperature of the pipe in the 180 ° bend, the evolution of the temperature is correct. A little difference appear in t=700, at this time the pressure change of evolution, in the experiment that change the flow rate, but in the model the flow rate is constant. To improve this result, the change of flow rate needs to be calculated.

Figure 8, show the same result, here the difference is even more big, it's an accumulation of all the effect in the pipe. But the evolution and the temperature is very close.

This result allows us to validate the model. The RMS error for the total point is 1.16 degrees Celsius, it's acceptable considering the error on the measurement. To improve the model, a more complex study is necessary. The change of the flow rate in the cycle need to be takes in account. For that, a coupling of the model with the condenser, the evaporator and the compressor is necessary.

5. Conclusions

Direct Expansion (DX) ground source heat pump is an interesting technology to develop solution for heating and cooling building. The literature review revealed a lack of scientific research and publication direct expansion geothermal heat pump systems. To develop tool to help the design of this technology, a model of a ground source heat pump need to be develop. In this study, a model of the ground exchanger is going to be presented in 1 dimension for a heating process. The model represents the phase change of the refrigerant, here Chlorodifluoromethane R22, with governing continuity, momentum and energy equations and with heat exchange between pipe and grout. A comparison between the model and experimentation was realised. The result allowed us to validate the model. The next step to improve the model is to link the model to the other component, like the exchangers with the water and the compressor to take account the change of the flow rate in the circuit and the change of the soil temperature.

6. References

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