Thermal performance of a co-axial borehole heat exchanger

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ABSTRACT. *This paper present result of thermal performance of a co-axial borehole heat exchanger for time varying inlet air temperature on a hottest and coldest day of the year 2015 at N.I.T Jamshedpur, India. Numerical method based on heat transfer correlation has been developed which validated with CFD simulation results. AICO has better performance because of lowering of outlet temperature during hottest day and increasing of outlet temperature in coldest day. Heat transfer to the soil has higher of 100W and lower short-circuiting through central pipe of around 400W difference in AICO (Annulus in Central Out) as compare to CIAO (Centre In Annulus Out).*

RÉSUMÉ. *Cet article présente le résultat des performances thermiques d'un échangeur de chaleur à forage coaxial avec une température d'air d'entrée variable dans le temps, lors de la journée la plus chaude et la plus froide de l'année 2015 à N.I.T Jamshedpur, Inde. Une méthode numérique basée sur la corrélation de transfert de chaleur a été développée et validée avec les résultats de la simulation CFD. AICO offre de meilleures performances en raison de la baisse de la température de sortie pendant la journée la plus chaude et de l'augmentation de la température de sortie en journée la plus froide. Le transfert de chaleur vers le sol a plus de 100W et moins de court-circuit à travers le tuyau central d'environ 400W de différence dans AICO (Annulus in Central Out) par rapport à CIAO (Centre In Annulus Out).*

KEYWORDS: *Borehole heat exchanger, thermal performance, CFD, Analytical method, AICO, CIAO.*

MOTS-CLÉS: *Échangeur de chaleur à forage, performances thermiques, CFD, méthode analytique, AICO, CIAO.*

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1. Introduction

Saving energy is one of the most important global challenges. A large portion of the global energy supply is used for space heating and cooling during summer and winter (Yang *et al.*, 2014). Due to this we facing lot of environmental issues like ozone depilation, climate change and increasing greenhouse gases etc. Ground couple heat exchanger is one of the alternative method used for space heating and cooling. The most common ground couple heat exchangers are horizontal and vertical types. Horizontal ground couple heat exchangers are laid below 2-3m depth at pipe of 60-100m. Vertical heat exchangers is deep the pipe with two common configurations such as U-tube and co-axial.

Soni *et al.* (2015) presented excellent review on ground couple heat exchangers. Zhao *et al.* (2007) performed an experiment to study heat transfer through outer wall of co-axial GCHE. Sharqawy *et al.* (2009) studied the effect of thermal resistance. Guillaume and Acuna *et al.* (2011) studied system by finite element software COMSOL and validated there result by experimentally. Zanchini *et al.* (2010) performed experimentally to study the effect of thermal insulation in central pipe. Christopher *et al.* (2011) did comparative study on co-axial and U-tube heat exchangers. Beier *et al.* (2013; 2014) and Acuna *et al.* (2013) worked on the temperature distribution with flow rate, grout with soil and only soil condition at study as well as transient condition. Benamer *et al.* (2015) has latest study on U-tube heat exchanger with fin using CFD software. Raymond *et al.* (2015) performed to decrease the thermal resistance by the using of internal pipe properties. Belolufi *et al.* (2017) investigated EAHE experimentally and numerically to improve the heat exchanger performance.

The present paper investigates thermal performance of co-axial ground heat exchanger using fluid as air for proper ventilation of houses during hottest and coldest day for the year 2015 at Jamshedpur, India.

2. Mathematical formulation

Vertical co-axial ground couple heat exchanger consists of two pipes given in figure 1. Inner pipe of diameter 0.0762m inserted in outer pipe of diameter 0.127m for a pipe length of 20m. The outer pipe is connected with soil with constant temperature of 26.29 ^{0}C is equal to annual average temperature of the year 2015 for the Jamshedpur (India).

The steady mathematical model is formulated based on energy balance at the given discrete model varying i from 1 to 2n shown in figure 2. In the figure 3 express the energy balance equation of annulus section and central pipe at various number of discrete points can be solve by matrix formulation.

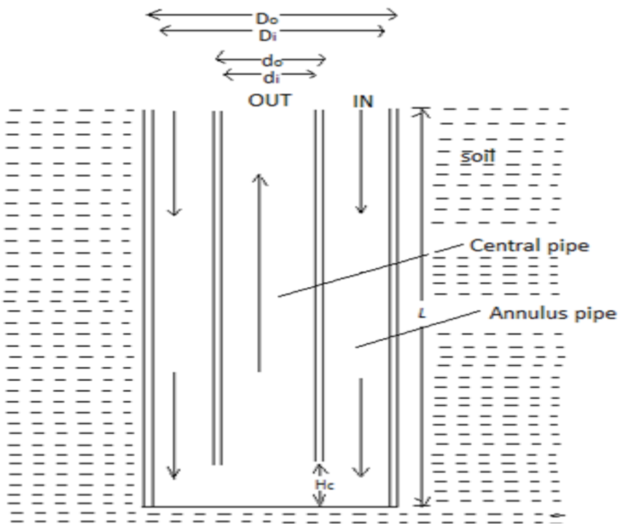

Figure 1. Schematic diagram of a coaxial borehole heat exchanger

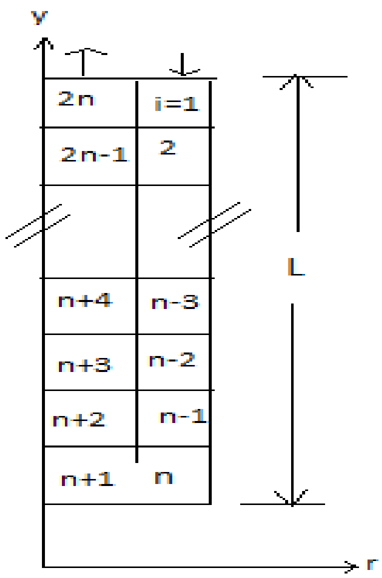

Figure 2. Discretion of vertical ground

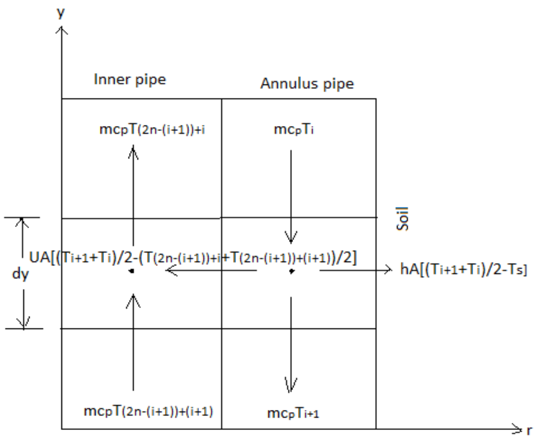

Figure 3. Energy balance for VGHE

Annulus pipe section

$$\begin{aligned} & mc_p(T_{i+1}-T_i)=hA[(T_{i+1}+T_i)/2-T_s] \\ & +UA[(T_{i+1}+T_i)/2-(T_{(2n-(i+1))+i}+T_{(2n-(i+1))+(i+1)})/2] \end{aligned} \tag{1}$$

Central pipe section

$$\begin{aligned} & mc_p(T_{(2n-(i+1))+i}+T_{(2n-(i+1))+(i+1)})= \\ & UA[(T_{i+1}+T_i)/2-((T_{(2n-(i+1))+i}+T_{(2n-(i+1))+(i+1)}))/2] \end{aligned} \tag{2}$$

Base section

$$T_{(2n-(i+1))+(i+1)}=T_{i+1} \tag{3}$$

$$UA=\frac{\ln(\frac{D_o}{D_i})}{2\pi k_a L}+\frac{1}{h_o A_o} \tag{4}$$

$$hA=\frac{1}{h_i a_i}+\frac{\ln(\frac{d_o}{d_i})}{2\pi k_c L}+\frac{1}{h_o A_o} \tag{5}$$

The heat transfer equation at central and annulus pipe can be define as,

$$h = \frac{Nu * k}{D_h} \tag{6}$$

The Nusselt number for central and annulus pipe is calculated using Gnielinski Correlation given in Shah and Sekulic, (2003),

$$Nu = \frac{(f/2)(\mathrm{Re} - 1000)\,\mathrm{Pr}}{1 + 12.7(f/2)^{1/2}(\mathrm{Pr}^{2/3} - 1)} \tag{7}$$

Here *f* is the friction coefficient of circular and non-circular pipe and determine using Bhatti-Shah correlation given in Shah *et al.*,

$$\begin{aligned} & f = A + B * \mathrm{Re}^{-1/m} \\ & where \\ & A = 0.0054; B = 2.3*10^{-8}; m = -2/3\left(2100 \le \mathrm{Re} \le 4000\right) \\ & A = 0.00128; B = 0.1143; m = 3.2154\left(4000 \le \mathrm{Re} \le 10^{7}\right) \end{aligned} \tag{8}$$

Design of CFD model

computational Fluid Dynamics (CFD) is the analysis of system involving fluid flow, heat transfer and associate phenomena by means of computer based simulation. The technique is very powerful and wide range of industrial and non-industrial application.

Computational design model

Present geometrical configuration sketch in the ANSYS workbench V17. Figure 4 shows 2-Dimentional axis symmetry co-axial earth air heat exchanger having inner pipe diameter 0.0762m with 0.127m of outer pipe having thickness of 0.0065m and 0.004m respectively. 20m of pipe length taken.

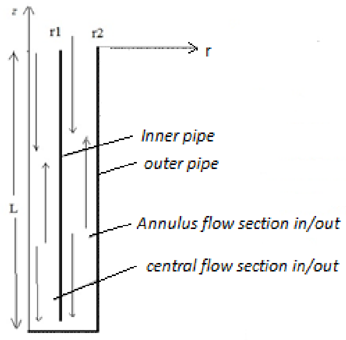

Figure 4. Sketch of the computational domain

3. Grid generation

Meshing of the system is performed under ANSYS ICEM CFD V17 software which is shown in figure 5. An unstructured grid is generated with the condition of fine relevance centre having cell size varied from 387172 to 988353 in four steps. It is found that after 683385 cells, variation of outlet temperature is less which is shown in table 1.

Table 1. Grid sensitivity test

No of cells	Outlet Temperature
387172	302
506814	302.08
687012	302.28
988353	302.31

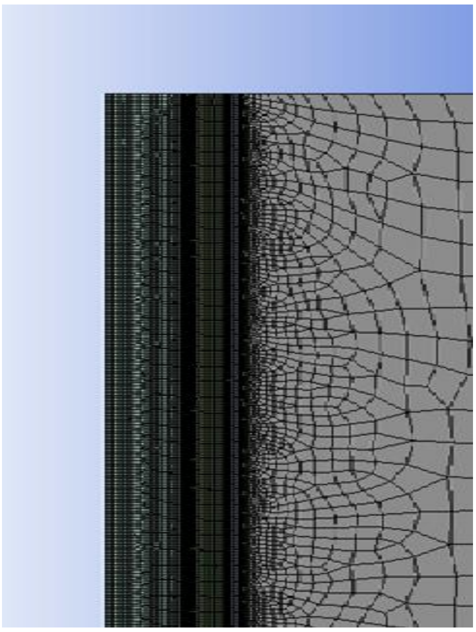

Figure 5. The grid system of computational domain

Governing equation

The general transport equations that describes the principal of the mass, continuity, momentum and energy can be express as:

$$\frac{\partial}{\partial t}(\rho\phi) + div(\rho u\phi) = div\ (\Gamma\ grad\phi) + S \tag{9}$$

The above governing equation for the given computational domain can be solving by finite volume method in ANSYS FLUENT V17 software. During process k-ε turbulent model with solution algorithm as SIMPLEC. The analytical model studied the iterative solution is continued until the residuals for all cell of calculation which is 1e-6 for continuity, k-epsilon, x-velocity, y-velocity, and energy equation.

4. Boundary condition

1.Inlet boundary: At the inlet of heat exchanger has uniformed mass flow rates of 0.1,0.06 and 0.02 Kg/s with physical properties of air remain constant and temperature is taken as time variant value of hottest and coldest day.

2. Outlet: outlet taken as zero gradient pressure.

3. Pipe temperature: Outer pipe is taken as 26.29^{o}C which is equal to annual average air temperature. This temperature is considering as soil temperature. the pipe has PVC material with isotropic and homogeneous in nature with physical properties is constant given in Table 2.

4. Air pipe interface: At air pipe interface couple heat transfer condition was taken.

Table 2. Properties of PVC pipe

Symbols	Value
ρ	1400
μ	1047
k	0.5

5. Results and discussion

The simulation has been run for AICO (Annulus IN and Centre out) and CIAO (Central IN and Annulus Out) condition. Figure 6 and 7 show variation of outlet air temperature of AICO system hottest day on 10th of June and coldest day 28th of December for Jamshedpur (India) at different mass flow rate. On the hottest day the outlet temperature decreases with decreasing mass flow rate. During morning and night different is minimum but at after noon the temperature difference is around 10^{0}C. Similarly, in case coldest day, temperature different is higher at morning and night and minimum in the afternoon.

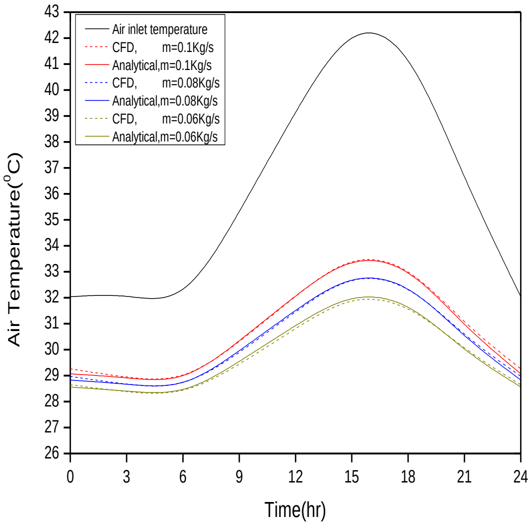

Figure 6. Temperature profile during hottest day at different mass flow rate

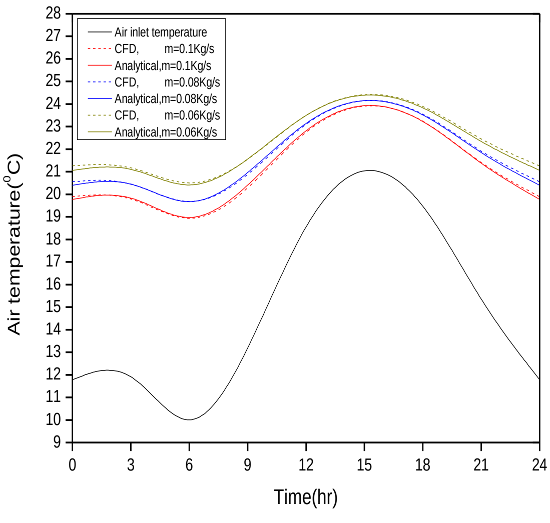

Figure 7. Temperature profile during coldest day at different mass flow rate

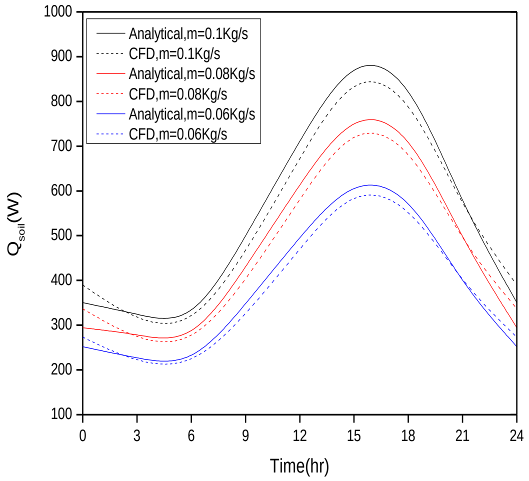

Figure 8. Heat transfer during hottest day at different mass flow rate

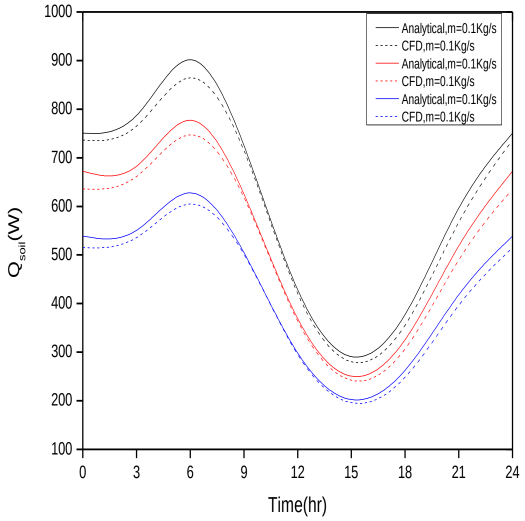

Figure 9. Heat transfer during coldest day at different mass flow rate

Figure 8 and 9 show the heat transfer on hottest and coldest day of AICO system. As the mass flow rate is decreasing, the heat transfer decreases because the temperature difference is minimum. At 0.1Kg/s mass flow rate has maximum heat transfer is 900W and minimum of 300W, whereas it drops to 600W is maximum and 200W is minimum at mass flow rate of 0.06Kg/s.

6. Conclusion

The present investigation reported results of thermal performance of vertical ground couple heat exchanger through analytical and CFD method. The result has nearly same at different flow conditions. AICO has better performance because of lower outlet temperature during hottest day and higher temperature in coldest day. heat transfer to the soil has higher of 100W and lower short-circuiting through central pipe of around 400W difference in AICO as compare to CIAO. Flow rate at lower value is consider because it gets the lower and higher temperature during summer and winter in both flow condition which is AICO and CIAO.

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NOMENCLATURE

A	Surface Area
a_i	Area of inner pipe of inner section
a_o	Area of inner pipe of outer section
A_i	Area of outer pipe of inner section
A_o	Area of outer pipe of outer section
d_i	Diameter of inner pipe of inner section
d_o	Diameter of inner pipe of outer section
D_i	Diameter of outer pipe of inner section
D_o	Diameter of outer pipe of outer section
f	Fraction factor
h_o	Heat transfer coefficient of outer pipe
h_i	Heat transfer coefficient of inner pipe
D_h	Hydraulic coefficient

m	Mass flow rate
H_c	Gap between central pipe and ground
Pr	Prandtl number
Re	Reynolds number
C_p	Specific heat
L	Length of pipe
i	Number of division
Nu	Nusselt number
T_i	Temperature at i position
K	Thermal conductivity of air
K_c	Thermal conductivity of central pipe
K_a	Thermal conductivity of annulus pipe
U	Heat transfer at central pipe
ρ	density
μ	viscosity
V	velocity
Φ	General variable