International Journal of Heat and Mass Transfer 126 (2018) 740–752

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Conjugate heat transfer in artificial ground freezing using enthalpy-porosity method: Experiments and model validation

Mahmoud A. Alzoubi, Aurelien Nie-Rouquette, Agus P. Sasmito *

Department of Mining and Materials Engineering, McGill University, 3450 University, Frank Dawson Adams Bldg., Montreal, QC H3A0E8, Canada

ARTICLE INFO

Article history:
Received 6 March 2018
Received in revised form 3 May 2018
Accepted 11 May 2018

Keywords:
Artificial ground freezing
Conjugate heat transfer
Enthalpy-porosity method
Porous media
Solidification

ABSTRACT

Artificial ground freezing (AGF) system is a temporary excavation-support method that is used in underground mines and tunneling projects to improve and stabilize ground structure, and to control groundwater seepage. The conjugate heat transfer between the bayonet freeze pipes and the ground plays a vital role in determining ice wall formation, heat extraction rate and closure time. In this study, a controlled laboratory scale AGF experimental rig is conceived and developed at Mine Multiphysics laboratory, McGill University. It is equipped with more than 80 temperature readings, thorough properties characterization, and an advanced instrumentation system to quantify the conjugate heat transfer process. We also developed a three-dimensional conjugate mathematical and numerical model of the bayonet freeze pipes and porous ground structure using enthalpy-porosity method. The model is further validated against global heat balance and local temperature distributions from our experiments at various operating conditions. Good agreement between model predictions and experimental data was achieved with $R^2 = 0.972$. The results indicate that higher coolant Reynolds number gives rise to a higher Nusselt number and, thus, higher heat extraction rate which is mirrored by a shorter closure time. Coolant Reynolds number is found to have a higher effect on the heat transfer performance as compared to coolant temperature and grounds initial temperature. Finally, the model is a reliable tool that can be extended and employed for design and optimization of industrial AGF system.

1. Introduction

Artificial ground freezing (AGF) was developed by Friedrich Poetsch in the 19th century to stabilize the construction of deep shafts in saturated soil [1]. The system, since then, has been used intensively in several applications such as underground mines [2], shaft sinking [3], civil and tunneling [4,5], maintaining the permafrost structure by implementing thermosyphon concept [6], and hazardous-waste management [7]. The AGF process has many advantages, as compared to other geotechnical support methods such as cement and chemical grouting, dewatering, and compressed air. It is compatible with wide range of soil types [8], has low effect on the ground structure (during and after the freezing process) [8,9], has a small impact on the environment [10], and it is a reliable method for high-risk applications such as uranium mines [11] and harmful-wastes management [12,13]. The concept of an AGF system is to circulate a sub-zero coolant in a network of pipes to freeze the surrounding saturated-soil. As the coolant flows through the pipes, it extracts heat from the ground and induces the gradual freezing of the groundwater. The quantity of extracted heat depends on the thermal interaction between the coolant's flow and the porous ground.

Several contributions have been made in literature to examine the AGF process analytically [14–16] and numerically [17–19]. Sanger and Sayles [14] solve the AGF process for vertical pipes by dividing the process into two main stages: (i) the frozen body is growing around the separate pipes; and (ii) the circular frozen body merged to form a continuous curtain. It was assumed that a neighbor freeze pipe does not affect the growth of the frozen body. Holden [15] extended Sanger and Sayles model by considering the contribution of a neighbor freeze pipe to the growth of frozen body in the first stage. Zhou et al. [16] studied AGF process for shaft sinking application. The study considered one freeze pipe and modeled it as an infinite line source using similarity type of general solution. Further analysis could also be performed using proper orthogonal decomposition (POD) reduced-order model in order to save the computational time [20]. Rouabhi et al. [17] studied the heat transfer in a porous ground structure during the salt-cavern leaching process. The process considered a single freeze pipe that is installed vertically in the ground. They built a 2D axisymmetric model using a semi-analytical approach to simulate the transient

---

* Corresponding author. Tel.: +1 (514) 398-3788.
E-mail address: agus.sasmito@mcgill.ca (A.P. Sasmito).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.059
0017-9310/

Nomenclature

$A_{p\upsilon}$	interfacial area
C	constant
c_p	specific heat capacity
G_κ	the generation of turbulence kinetic energy
$\mathbf{g}$	gravitational acceleration
h	specific enthalpy
$\hbar$	heat transfer coefficient
K	permeability
k	thermal conductivity
L, ℓ	length
$\dot{m}$	mass flow rate
Nu	Nusselt number
P	pressure
Pr	Prandtl number
$\dot{q}$	heat flux
R^2	coefficient of determination
Re	Reynold's number
S	source term
S_p	Sparrow number
T	temperature
t	time
$\mathbf{U}, \mathbf{u}, \mathbf{v}$	velocity
V	volume
$\dot{V}$	volumetric flow rate

Greek letter

β	thermal expansion coefficient
γ	liquid fraction within pore fluid
δ	liquid fraction in a volume element
ϵ	rate of dissipation
ε	porosity
θ	diffusive coefficient
κ	turbulent kinetic energy
μ	viscosity
ρ	density
σ	turbulent Prandtl number
φ	dependent variable
Ψ	volume averaged quantity
ψ	local quantity

Superscripts

L	latent
S	sensible

Subscripts

c	coolant
e	effective
g	ground
in	inlet
$init$	initial
ℓ	liquid
ℓ	length – Eq. (27)
m	mushy
out	outlet
p	particle
ref	reference
s	solid
t	turbulent
υ	void
w	wall

heat transfer. Papakonstantinou et al. [18] examined the AGF process for horizontal pipes installation that is usually used in tunneling projects. They validated their numerical model against in situ temperature measurements. Vitel et al. [19] developed a conjugate 2D axisymmetric model to simulate AGF process for a singular freeze pipe. They studied the effect of coolants' properties on the efficiency of the freeze pipe in terms of the ice growth. In these studies [14–19], conductive heat transfer has been assumed as the primary mechanism for energy transfer, whereas convective heat transfer is low enough to be neglected. However, under certain conditions, such as high porosity or groundwater seepage, convective heat transfer become more significant and should be considered in the calculations [21,22].

Recent studies, such as [23,2,24–26], included the convective heat transfer in the mathematical models. Vitel et al. [2] extended their previous work [19] by studying the performance of AGF process in fractured sandstone. They studied the effect of fractures on the ice growth within the AGF process. Ou et al. [23] examined the performance of AGF process in tunneling project. They studied the time that is required to achieve the minimum thickness of ice wall. Another study from Vitel et al. [24] modeled the transient heat transfer of AGF under high seepage velocities. The study showed the influence of groundwater seepage on the growth of the frozen body. Marwan et al. [25] used the ant colony method in their work to optimize the spacing between horizontal freeze pipes in tunneling projects. The optimization method along with their numerical model reduced the freezing time as compared to an equal spacing of freeze pipes. Rouabhi et al. [26] investigated the effect of the salinity of groundwater on the performance of AGF process. They found that water salinity affects the capillary pressure in porous media and on the latent heat of fusion. These studies used the effective (apparent) heat capacity assumption; an approach used to simulate the latent heat of fusion as a part of the fluid heat capacity. This procedure, however, requires careful consideration of the temperature, velocity, and latent heat evolution in the phase-change zone [27]. Alternatively, Voller and Prakash [28] proposed a modeling methodology called enthalpy-porosity method, where the water-ice phase-change interface is modeled as a mushy zone. The transformation from water to ice in this zone is considered as a porous medium, where a modified Darcy source term (called here: mushy source term) is used to simulate motion in the phase-change region. This approach shows some advantages in terms of simplifying the numerical modeling requirements without compromising the accuracy of the results.

The reliability of mathematical models can be assessed by validating computational results with the measurements of an experiment that is carried out under controlled environment. Several experiments have been conducted to mimic the AGF system. Ständer [29] performed one of the first systematic experiment on AGF. The tests were performed either with a single freeze pipe or with a group of freeze pipes, which were arranged in a circle to mimic the underground tunnel usage of AGF. The results were presented by means of contours showing the ice growth around the freeze pipes. Victor [30] used a similar setup as Ständer, but with seepage flow included. The experiment of Pimentel et al. [31,32] is, to our knowledge, the only reference that has been used to validate the mathematical models of the recent, respective studies. Pimentel et al. examined the adverse effect of groundwater