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Modeling heat transfer between a freeze pipe and the surrounding ground during artificial ground freezing activities

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ABSTRACT

The artificial ground freezing method (AGF) is widely used in civil and mining engineering. In AGF numerical models, the thermal boundary conditions at the freeze pipe wall, whether they be expressed in temperature or in flux, are generally determined based on in situ measurements, which are not readily available. The purpose of this paper is to study the complete heat transfer problem in order to develop a thermal model that can be easily used in field applications. In this numerical model, the freeze pipe and the surrounding ground are considered in a coupled way. External data of temperature or flux at the pipe wall is therefore not needed to predict the temperature evolution in the ground. Moreover, the developed model can be used to conduct parametric studies on operating conditions, refrigerant type, system geometry or ground properties. Indeed, the reduction of the heat transfer problems in the ground and in the pipe into highly time-saving 1D problems allows the rapid resolution of many calculations. Then, the developed model can also find its use in the optimization and the design of AGF systems.

1. Introduction

Patented by Poetsch in Germany in 1883, the artificial ground freezing technique (AGF) appeared 150 years ago in coal mines in South Wales. Nowadays, it is particularly widespread in civil engineering (tunneling, landslide stabilization, underpinning), mining engineering (shaft sinking) and environmental engineering (containment of hazardous waste) [1]. It is generally used for its two conjugated effects. Firstly, it reduces the ground permeability, which mitigates water seepage and inflow into underground workings. Secondly, it allows to improve the mechanical properties (strength and stiffness) of the ground and thus to increase the stability of future excavations.

The principle of AGF is to circulate a fluid coolant through a pipe network in the ground to be frozen. As it flows in the pipes, the refrigerant extracts heat from the surrounding ground and pore liquid water gradually turns into ice. The quantity of extracted heat depends on the cooling conditions. Therefore, an estimation of the temperature distribution in the ground would require an understanding of the thermal processes which occur inside the freeze pipes. In common AGF numerical models, these processes are not simulated and thermal boundary conditions at the freeze pipe wall, based on external data defined from in situ measurements, are merely included (e.g. [2–5]). However, these measurements, whether they be expressed in temperature or in flux, are not readily available.

Since the first thermo-hydraulic coupled model of ground freezing elaborated by Harlan [6], a lot of effort has been put into the development of models that take into account coupling between thermal, hydrogeological and mechanical mechanisms (e.g. [4,7–9]). In contrast, the influence of the freezing conditions has not been studied extensively despite its importance for the optimization of ground freezing systems. A few works briefly present parametric studies of the system geometry (e.g. [10–13]) or of ground properties (e.g. [14]). Information about the influence of the coolant parameters seems to be very limited. Only the effect of the coolant temperature was studied [11,14] and, apart from [10], the effect of the flow rate of the coolant, or of its thermophysical properties, does not seem to have been studied.

The purpose of this study is to develop a new approach where the freeze pipe and the surrounding ground are considered in a coupled way. The numerical model simulates in an iterative manner the heat transfer between the pipe components, between the pipe and the ground and in the ground, while the coolant flows. Temperature or flux data at the pipe wall is therefore not needed to model the temperature evolution in the ground and only initial and boundary conditions are required.

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Nomenclature

Greek letters

$\alpha, \beta, \gamma, \varpi$	coefficients of the differential equations governing T_c and T_a
Δt	time step size
ε	level of accuracy
$\kappa, \overrightarrow{K}$	integrands of the general form of a conservation law
λ	thermal conductivity
μ	dynamic viscosity
φ	mass density of Φ
φ^*	source mass density
$\hat{\pi}_\alpha$	rate of phase α production
ρ	density
ρ^α	apparent density of phase α
Σ	cross section
τ	friction tangential stress
Φ	extensive physic property
$\overrightarrow{\Psi}$	surface flux density
ψ	surface density of heat flux exchanged between the fluid and the wall
$\widehat{\Psi}_\alpha$	interfacial exchange of flux for phase α
Ω	domain of integration

Latin letters

$\mathcal{A}$	cross sectional area
C_f	friction coefficient
c_p	specific heat capacity at constant pressure
D	diameter
$\overrightarrow{e_z}$	unit vector in the direction of the z-axis
g	specific Gibbs free energy
h	specific enthalpy
$\hbar$	overall heat transfer coefficient
h_{ij}	heat transfer coefficient
L	length
m, P	freezing characteristic curve parameters
Nu	Nusselt number
n	porosity
n_α	volumetric content of phase α
$\vec{n}$	unit exterior normal vector
$\mathcal{P}$	perimeter
p	pressure
Pr	Prandtl number
Q	mass flow rate
r	radius
R	thermal resistance
Re	Reynolds number
r, z	coordinates
s	specific entropy
S_λ	degree of liquid water saturation
T	temperature
t	time
t^*	previous time step
v	velocity
$\mathcal{V}$	volume

Subscripts

a	annular
α	phase
c	central tube
γ	ice
eq	apparent properties of the ground
g	geothermal
i	inner
ℓ	lateral
L	laminar flow
λ	liquid water
m	model
o	outer
p	pipe
σ	soil particle
T	turbulent flow
w	wall

Superscripts

0	reference
h	heated
w	wetted

In the following, the physical system we are dealing with is described in a first part. In a second part, the governing equations in both the pipe and the ground are presented, along with the numerical implementation of the model. The third part deals with the simplification of the 2D axisymmetric heat transfer problem in the ground around the well into a 1D problem. The fourth part discusses the interest of our model compared to the case where simple boundary conditions are considered in the ground model. In part 5, the results of a parametric study highlight the influence of operating conditions. The final part of the paper aims at showing the importance of the effect of latent heat during the ground freezing on the evolution of the ground temperature.

2. Heat transfer in and around the freeze pipe

2.1. Physical model

The freeze pipes used in AGF consist of two concentric tubes. The coolant is usually injected in an open-ended central tubing and flows back through the closed-ended annular space. The principle of circulation is illustrated in Fig. 1(a). Two mains types of refrigerant are used: secondary coolants and expendable refrigerants [1].

A secondary coolant circulates in a closed circuit: it is cooled at the surface in a refrigeration plant – ammonia is often used as the cooling agent – and sent underground in freeze pipes before returning to the freeze plant where it is re-cooled. The refrigerant is generally calcium chloride brine ($CaCl_2$) and its temperature in the freeze pipes ranges from −20 °C to −40 °C. Other circulating coolants such as glycols, hydrocarbons, alcohols or other salt brines are sometimes employed in a similar way. Despite their interesting properties, some of them are flammable and/or toxic and may thus be avoided.

In the case of expendable refrigerants, where liquid nitrogen (LN_2) is often used, there is no refrigeration plant since LN_2 is directly supplied into the freeze pipes. It starts to vaporize in the pipe at −196 °C and the exhaust gas is released in the atmosphere. Another expendable coolant is sublimating carbon dioxide but it is thermally less efficient than LN_2 and harder to control [1]. Due to the extremely low coolant temperature, LN_2 freezing is very fast compared to brine freezing. However, its use is limited because of its high cost.