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Natural convection around a vertical cylinder (thermal probe) immersed in a porous medium

Sandra Corasaniti, Fabio Gori *

University of Rome "Tor Vergata", Department of Industrial Engineering, Via del Politecnico 1, 00133 Rome, Italy

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ABSTRACT

Natural convection around a vertical cylindrical, immersed in a fluid-saturated porous medium, is investigated experimentally. The porous medium is made of glass beads with particles of the same diameter, 3 mm, and is saturated with water. The vertical cylinder, with diameter of 1.5 mm and long 150 mm, is a thermal probe, containing an electric heater and a thermocouple. Natural convection around the vertical cylinder is investigated experimentally with the help of three temperature sensors, at different heights on the external surface of the cylinder. Average and local Nusselt numbers along the vertical cylinder are calculated and compared with the available theoretical-numerical data of the literature.

1. Introduction

Heat transfer in a fluid-saturated porous medium is an important topic because of the several applications involved, e.g. geophysics, thermal insulation of buildings, geothermal engineering, filtration processes, ground water pollution and heat storage systems. Natural convection around a vertical cylinder is important for several heat transfer applications, as, for example, the calculation of the heat losses from vertical pipes, and cylindrical elements of heating or cooling devices.

Minkowycz and Cheng [1] presented a numerical study of free convection around a vertical cylinder embedded in a porous medium, comparing local and nonlocal similarity methods of solutions. Few years later, the same authors [2] studied the free convection along a vertical plane in a porous material, and solved the problem through the local non-similarity approximation to the third level of truncation. Analysis of mixed convection along a horizontal heated surface, with the wall temperature depending on the distance, was carried on later with local non-similarity methods [3–4].

Steady-state natural convection in a concentric vertical annulus, filled with a saturated porous medium, was investigated experimentally, with the inner wall heated [5], and the solid-fluid combinations indicated a divergent behavior in the Nusselt-Rayleigh numbers curve. Transient and steady-state thermal fields throughout an annular region bounded by vertical coaxial cylinders were investigated in [6]. The experimental results showed that the steady-state surface temperature increases with the increase of the vertical distance, due to the buoyancy-driven up-flow. The combined heat and mass transfer along a vertical cylinder in a porous medium and the effects of curvature and concentration were investigated in [7]. Heat and mass transfer in natural convection inside a porous media was studied analytically for a paraboloid, with constant temperature and concentration, and a cylinder, with linear temperature and concentration variation [8]. Numerical solutions showed the influence of non-Darcian flow phenomena in fluid flow and heat transfer [9]. Steady state two-dimensional natural convection flow through a porous medium, bounded by a vertical infinite porous plate, and in presence of radiation, was studied in [10].

Transient heat transfer in a porous medium, stored inside a cylinder and cooled from the external wall, was investigated by considering natural convection within the medium [11]. A numerical study of heat transfer in a conical annular cylinder, filled with a saturated porous medium, was carried on in [12], and the results were discussed for different values of the geometric and physical parameters, with the emphasis on the cone angle of the cylinder. Free convection around a vertical cylinder, embedded in a porous medium, was studied in [13], assuming that solid and fluid were not in local thermal equilibrium, and using a two-temperature model.

A thermal probe, built in laboratory [14], was employed to measure the thermal conductivity and diffusivity of soils, [15–17], to investigate the transition from conduction to convection [18], to evaluate the thermal properties of insulating materials and porous media, [19–23]. Later on, the experimental results, obtained with the thermal probe, have been used as reference for numerical and theoretical solutions of natural convection along the cylindrical surface of the thermal probe [24–25], while the idea of the thermal probe was proposed in [24] to be used for "in situ" experiments in Mars regolith.

The present investigation is aimed at evaluating experimentally the convective heat transfer coefficient along the cylindrical surface of a vertical cylinder (thermal probe) immersed in glass beads, saturated with

* Corresponding author.
E-mail address: gori@uniroma2.it (F. Gori).

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water, and at comparing the data with the theoretical-numerical predictions of the literature.

Nomenclature

Latin

c	specific heat at constant pressure, J/(kg K)
d	glass beads diameter, m
D	probe diameter, m
Gr	Grashof number
h	heat transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
K	permeability, m^{-2}
i	electric current intensity, A
h	convective heat transfer coefficient, W/(m^2 K)
H	probe length, m
Nu	Nusselt number
Pr	Prandtl number
q	heat flux, W/m^2
Q	heat power, W
r	radius, m
R	electric resistance, Ω
Ra	Rayleigh number
t	time, s
T	temperature, K or °C
TC	thermocouple
z	axial coordinate, m

Greek

α	thermal diffusivity, m^2/s
β	coefficient of thermal expansion, K^{-1}
Δ	difference
ε	porosity
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

Subscript

av	average
e	external
eff	effective
f	undisturbed fluid
i	internal
p	particle
s	surface
th	theoretical

2. Experimental set-up

The thermal probe is employed to investigate experimentally the problem. The experimental set-up is made of a container, with the porous medium and the instrumentation, sketched in Fig. 1.

The thermal probe, with diameter of 1.5 mm and length 150 mm, is set on the axis of a cylindrical container, high 155 mm and with diameter of 300 mm, where glass beads of the same diameter, 3 mm, is saturated with water. The thermal probe contains a thermocouple and a platinum wire heater, spiralled around it. A thermocouple is set on the

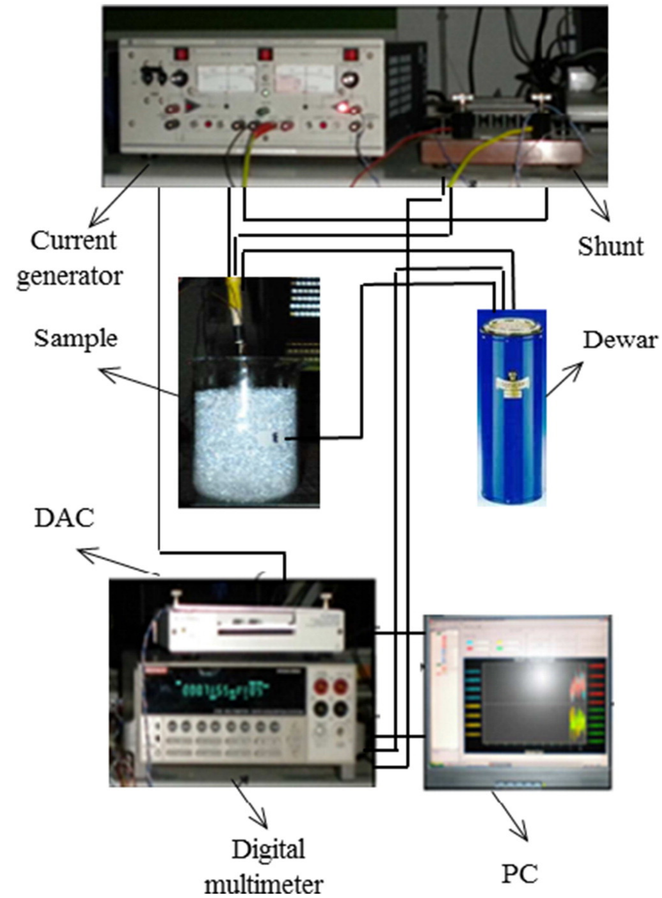

Fig. 1. Experimental setup.

internal wall of the container (Wall TC) to control the global heating of the sample. Three additional thermocouples are set on the external surface of the probe, at three different heights. The thermocouple at $z = 3/4H = 112.5$ mm is called the top one (Top TC), that at $z = H/2 = 75$ mm the middle one (Middle TC), and that at $z = H/4 = 37.5$ mm the bottom one (Bottom TC). The thermocouple inside the probe allows the measurement of the thermal conductivity of the sample with the perfect line source method [27].

Fig. 2 reports a sketch of the thermal probe with the positions of the three thermocouples along its external surface. A step heating in the

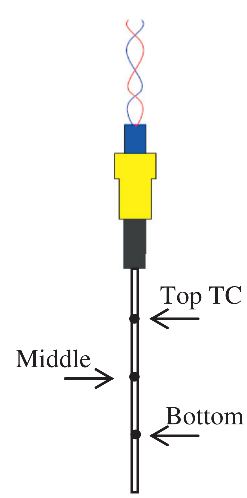

Fig. 2. Sketch of the thermal probe and locations of the three thermocouple along the external surface.