International Journal of Thermal Sciences 99 (2016) 71–84

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Numerical study of the sensing mechanism of the oxygen concentration sensor based on thermal magnet convection

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ARTICLE INFO

Article history:
Received 28 December 2014
Received in revised form
8 July 2015
Accepted 12 August 2015
Available online xxx

Keywords:
Sensing mechanism
Oxygen
Thermal magnet convection
Magnetic induction
Numerical simulation

ABSTRACT

Magnetic oxygen concentration analyzer based on thermal magnet convection is suitable for automatic measurement of the oxygen concentration in all kinds of industrial gases. In this paper, the sensing mechanism of the analyzer is numerically studied. The studied analyzer includes a horizontal circular tube, and an external magnet field produced by two permanent magnets. The results show the sensing mechanism of the analyzer is that thermal magnet convection greatly increases the average velocity of fluid flow through the tube and increases slightly the heat transfer coefficient. As results the wall temperature decreases, and this temperature decrease is strongly related with oxygen concentration. If the wall temperature is measured, the concentration of oxygen can be obtained. It is found that only when the pressure difference between the inlet and the outlet of the tube is less than 0.014 Pa, the thermal magnetic convection is obvious. The relationship between the wall temperature change and the oxygen concentration can be in a good linearity if the oxygen concentration region is divided into two regions: 0–30% and 30%–100%. The resolution of the sensor based on thermal magnetic convection is about 0.0067% for the configurations studied.

1. Introduction

In many industrial processes the oxygen concentration in gases needs to be measured. Thus measurement of oxygen concentration is critical. Currently, there are two main principles to measure the oxygen concentration. One is an electrochemical method, such as zirconium oxide analyzer [1,2]. The other is physical method, such as magnetic oxygen analyzer [3]. Thermal magnetic oxygen concentration sensor uses physic mechanism to measure the oxygen concentration. Utilizing the features that oxygen is a paramagnetic substance while most other gases are diamagnetic and the magnetic susceptibility of oxygen is apparently higher than other gases. The sensing principle is based on the convection in gases under actions of magnet gradient and temperature gradient. The oxygen magnetic susceptibility change with temperature plays a key role in thermal magnet convection. Indeed, through the temperature dependence of the magnetic susceptibility, the temperature gradient combined with magnetic field gradient works as a driving force. This force is the basis to produce thermal magnetic convection. Compared with the electrochemical analyzer, thermal magnetic oxygen concentration analyzer has the advantage of high life.

The thermal magnet convection has been attracted more attention with the development of strong magnet. Wakayama's group [4–9] has reported various findings on the phenomena associated with magnetizing force. The magnetic attractive force acting on paramagnetic oxygen gas has been found to affect air convection and promote combustion. Jovanovic [10] verified that weak non-conductive magnetic ions in a magnetic field can be exempted from the effects of gravity, and his results show that a steady flow of ions in the magnetic field can be controlled by the magnetizing force. As the temperature of non-conductive medium changes, the magnetizing force changes also. Tagawa et al. [11] has presented a model for thermo-magnetic convection and carried out numerical simulations in a cubic cavity. Wrobl reported that for the presence of paramagnetic magnetic field space, the magnetic field can strengthen or weaken the fluid convection or heat transfer process [12]. Wang et al. [13] shows that both the magnetic force and the inclination angle have significant effect on the flow field and heat transfer in porous medium. Yang et al. [14] studied

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http://dx.doi.org/10.1016/j.ijthermalsci.2015.08.006
1290-0729/

Nomenclature

B_r	magnetic induction [T]
C	Curie constant
c_p	specific heat capacity [kJ/(kg·K)]
D	tube diameter [m]
$\mathbf{F}$	force vector [N/m^2]
F	the area of heat transfer [m^2]
h_{local}	convective heat transfer coefficient at every measured point [W/(m^2·K)]
$\mathbf{H}$	magnetic field intensity [A/m]
$\bar{h}$	average heat transfer coefficient [W/(m^2·K)]
h	convective heat transfer coefficient [W/(m^2·K)]
L	length of the tube [m]
m	magnetic moment [A·m^2]
M	magnetization [A/m]
Nu_{local}	local Nusselt number $Nu = h_{local} D/\lambda$
Nu_{ave}	average Nusselt number
Pr	Prandtl number $Pr = \nu/\alpha$
p	static pressure [Pa]
q	heat flux [W/m^2]
Q	heat transferred by fluid [W]
$\mathbf{r}$	position vector ($\mathbf{r}^2 = x^2 + y^2 + z^2$) [m]
R	distance ($R^2 = (x - x')^2 + (y - y')^2 + (z - z')^2$) [m]
R_0	resistance value at 0 °C [Ω]
R_t	resistance value at t °C [Ω]
S_ϕ	generalized source term
T	temperature [K]
T_w	temperature of the tube wall [°C]
T_f	averaged temperature of the fluid [°C]
T_0	inlet temperature [K]
T_c	reference temperature [K]
V'	infinitesimal volume [m^3]
u_i, u, v, w	components of velocity vector [m/s]
x_i, x, y, z	coordinate axes [m]
Y_1	volume percentage of oxygen

Greek symbol

α_1, α_2, α_3	the conversion factor of calculation plane and physical plane
α	thermal diffusivity [m^2/s]
$\acute{\alpha}$	temperature coefficient of resistance [1/°C]
β_1, β_2, β_3	the conversion factor of calculation plane and physical plane
β	coefficient of thermal expansion [1/K]
γ_1, γ_2, γ_3	the conversion factor of calculation plane and physical plane
Γ^ϕ	generalized diffusion coefficient
κ_1	volume magnetic susceptibility of oxygen
κ_2	volume magnetic susceptibility of nitrogen
κ	volume magnetic susceptibility of mixed gas
λ	thermal conductivity [W/(m·K)]
μ	dynamic viscosity [Pa•s]
μ_0	magnetic permeability of vacuum [$4\pi \times 10^{-7}$ H/m]
ν	kinematic viscosity [m^2/s]
ξ, η, ζ	coordinates axes in computational space
ρ	density [kg/m^3]
ρ_0	density at reference temperature [kg/m^3]
ϕ	common variables
φ_1, φ_2, φ_3	the conversion factor of calculation plane and physical plane
χ_g	magnetic susceptibility per unit mass [m^3/kg]
χ_c	magnetic susceptibility at reference temperature [m^3/kg]

Subscripts

ave	average
in	inlet
local	local value
m	magnetization force
out	outlet
w	wall surface
i	1,2,3

numerically the air natural convection in a 2D square enclosure by the action of two different permanent magnet systems. The results show that different magnetic field can be supplied by different permanent magnet system configurations in the concerned enclosure, and different magnetic forces can be formed to control the air natural convection.

Available literatures have disclosed deeper insights on the mechanism of thermo-magnetic convection, and have made great effort to optimum the configurations in which thermo-magnetic convection occurs. However, few papers reported the detailed sensing mechanism of the oxygen concentration sensor based on thermal magnet convection, even though such oxygen concentration sensor has been used many years. It is expected that further studies on the detailed sensing mechanism will help improving the quality of the sensor. Motivated by this, the present paper reports the numerical results of the detailed sensing mechanism of the oxygen concentration sensor based on thermal magnet convection.

2. Mathematical model

The systems of the sensor considered are shown schematically in Fig. 1. The dimension of the tube along the z direction is 28 mm long. The fluid in a tube is heated on the tube wall in the segment AB. A point is located at $z = 5.5$ mm, B point is located at $z = 15.5$ mm. The tube with diameter 6 mm is positioned in the gap of two same size permanent magnets arranged face to face so that the fluid is subjected to non-uniform magnetic field. The geometry of the magnet is shown in Fig. 1, the length is 10 mm, and the height is $5 + 4 = 9$ mm, the width is 8 mm, the angle is about 38°. The direction of the main magnetic field is parallel to y axis. When the gas mixtures flow through the part of the tube heated by electricity wire (AB segment, its length is 10 mm), their temperature rises. According to the Curie's law, the magnetic susceptibility of paramagnetic gas such as oxygen gas is inversely proportional to absolute temperature, thus, a driving force similar to buoyancy force is produced. A flow induced by this force is superimposed to the original flow. The resulting flow passes through the tube part, the temperature of the segment AB changes. The change of the wall temperature represents the oxygen concentration.

2.1. Magnetic field model

Permanent magnets are used in many applications. Their general need for dimensioning and optimizing leads to the development of various magnet field calculation methods [15]. Determination of the magnetic field in the region near the permanent magnets needs the presumption that the magnetization **M** of the permanent magnet is known. The method based on a system