International Journal of Heat and Mass Transfer 83 (2015) 212–221

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Feasibility study of electromagnetic driven dream pipe

Masao Furukawa [*], Mimpei Morishita, Shuichi Yokoyama

Department of Electrical Systems Engineering, Kogakuin University, 1-24-2, Nishi-Shinjuku, Shinjuku-ku, Tokyo 163-8677, Japan

ARTICLE INFO

Article history:
Received 22 April 2013
Received in revised form 24 November 2014
Accepted 24 November 2014
Available online 17 December 2014

Keywords:
Dream pipe
Forced oscillation
Electromagnetic drive
Enhanced heat transfer

ABSTRACT

Dream pipes, a kind of forced oscillatory heat pipes, necessarily require some driving mechanisms for oscillations of enclosed working fluids. Commonly fitted up are mechanical shakers but not suited for practical use because of becoming quite large in volume. Proposed in this study is an innovative type of dream pipe with an electromagnetically actuated oscillating disk. The driving principle basically follows Lorentz force generated upon electric wires set on the disk, in the radial direction of which a periodically varying magnetic field is formed by applying the three-phase alternating current. Feasibilities of this new device are theoretically examined by analyses from both thermal and electrical points of view. Heat transfer analysis is first made to determine the required driving force, from which the tidal displacement of the fluids is derived to show a resulted possible oscillation amplitude. Joule heat minimization analysis is then made to specify a suitable couple of the applied direct and alternating current voltages. Such specified voltages may go down to a lowest level by selecting the driving frequency to become an intrinsic one. The specific power, defined as the power to heat ratio, is introduced as a performance index of that device. Numerical results show that less specific power than 0.10 is possible in most of supposed design cases and that the required magnetic flux density is far smaller than 0.5 T. It is thus concluded that the electromagnetic driven dream pipe is realizable. A 400 W m class dream pipe of electromagnetic drive is then design-specified as a demonstrative example.

1. Introduction

Availability of oscillatory pipe flows was first mentioned by Chatwin [1] and then by Watson [2]. They mathematically demonstrated that reciprocating flows make a remarkable contribution to longitudinal mass dispersion. Kurzweg recognized that heat diffusion might also be enhanced by induced oscillatory flows since their exists an analogy between mass transfer and heat transfer. Kurzweg [3–6] and his coworkers [3,4] thereby made a series of experimental/ theoretical studies on enhanced heat conduction by sinusoidal oscillations. A novel type of heat transfer device, named dream pipe, was thus invented by Kurzweg [7]. This attracted much attention of researchers. Kaviany [8] and Kaviany and Reckker [9] investigated possibilities of dream-pipe- based heat exchangers. Zhang and Kurzweg [10,11] made numerical studies to appropriate dream pipes to enhanced thermal pumping. Katsuta et al. [12] experimentally demonstrated the workability of dream pipes with a model almost identical with Kurzweg's one. Expecting much higher thermal conductivities, Nishio et al. [13] proposed a phase-shifted dream pipe. Rocha and Bejan [14] composed a model applicable to geometric optimization of parallel tubes forming a dream pipe. It therefore seems that dream pipe has already arrived at a technology readiness state.

It is however noted that most of studies mentioned above [3–14] were done in late 1980s to early 2000s and that no dream pipes have been put to practical use in the past. The reasons why no remarkable progress has recently been made in the dream pipe technology are:

(1a) Mathematical expressions of Watson's formulas [2] and those transformed by Kurzweg [4–6] and then recomposed by Furukawa [15] are too sophisticated to actually calculate.
(1b) Computational modeling by Ozawa and Kawamoto [16] and analytical modeling by Takahashi [17] are also unsuitable for design calculations.
(2) Mechanical shakers for liquid oscillations usually consume a considerable amount of electrical power and become so bulky to set in a limited space, but no means taking the place of them have not been presented so far.
(3) Self-excited oscillatory heat pipes invented by Akachi [18,19] in early 1990s, now simply called OHP/PHPs (oscillating/pulsating heat pipes), won favor of researchers [20,21],

---

[*] Corresponding author. Tel.: +81 3 3342 1211; fax: +81 3 3342 5304.
E-mail address: au40740@ns.kogakuin.ac.jp (M. Furukawa).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.11.072
0017-9310/

Nomenclature

A	one-sided or cross-sectional area, m^2
a	tube inside radius, m; or coefficient paired with b in Eq. (9), s
B	magnetic flux density, T
b	coefficient paired with a in Eq. (9), s
c	multiplier noted as c_t in Eq. (9) or as c_m in Eq. (10), dimensionless
D	tube inside diameter, m
E	required electric power, W
F	driving force, N
F_M	magneto-motive force, A
f	driving frequency, Hz
H	intensity of magnetic field, A/m
I	electric current, A
k	thermal conductivity, W/m K
L	tube length, m
ℓ	oscillating disk size, m
m	exponent specifying test function in Eq. (9), dimensionless
N	number of tubes, wires, or windings, dimensionless
P	pressure gradient, Pa/m
p	pressure, Pa
Q	heat load, W
Q_J	Joule heat, W
R	relative increase of thermal diffusivity, dimensionless
R_E	electric resistance, Ω
r	radial distance, m; or normalized resistance, dimensionless
T	temperature, K
t	time, s
V	voltage, V
w	velocity, m/s
z	axial distance, m

Greek letters

Γ	temperature gradient, K/m
ΔT	temperature difference, K
ΔV	tidal volume, m^3
Δz	tidal displacement, m
η	specific power, dimensionless
θ	angular position, rad; or temperature field, m
κ	thermal diffusivity, m^2/s
μ_0	magnetic permeability of air, $4\pi \cdot 10^{-7}$ H/m
ν	kinematic viscosity, m^2/s
ρ	mass density, kg/m^3
σ	electric conductivity, 1/Ωm
τ	oscillation period, s
ϕ	cross-sectional area ratio, dimensionless
ω	angular frequency, rad/s

Subscripts

A	coil A, appended to F_M
AC	alternating current, appended to V
B	coil B, appended to F_M; or tube bundle, appended to A
C	coil C, appended to F_M
CR	cold reservoir, appended to T
D	oscillating disk, appended to A or ϕ
DC	direct current, appended to V
e	effective, appended to k or κ
HR	hot reservoir, appended to T
ℓ	leading wire, appended to A, I, N, R_E, r, or σ
m	coil, appended to I, N, R_E, or r
min	minimum, appended to E, F, Q_J, V, or η
n	viscosity-based, appended to ω
opt	optimal, appended to f
t	diffusivity-based, appended to ω
3ϕ	three-phase, appended to B or I
∞	mainstream, appended to T
$\perp$	tube cross-sectional, appended to A

Superscripts

$(\bar{\ })$	characteristic, appended to w; peak value, appended to B, F, F_M, H, or I; direct current, appended to V; or standard, appended to R_E or Δz
$(\tilde{\ })$	alternating current, appended to V
$(\hat{\ })$	possible, appended to w or θ
$()^*$	reference, appended to R_E or V
$(\tilde{\ })^*$	determined by Galerkin method, appended to a or b

Abbreviations

AC	alternating current
DC	direct current

and thereby their technical interest turned to OHP/PHPs rather than dream pipes.

Nevertheless, if some solutions should be found out, dream pipes would be serviceable for industrial use. As for Point 1, design formulas, readily calculable and highly accurate, have recently been presented by Furukawa [22]; who solved momentum-energy equations of the same form as Watson's [2] by using Galerkin method [23,24], a kind of variational technique. This greatly facilitates design calculations. As for Point 2, Furukawa [22] also numerically demonstrated the effectiveness of piezoelectric drives employed as a non-mechanical driving way with an expectation of less power and small volume. Regarding Point 3, OHP/PHPs can surely serve electronics cooling as most effective heat sink devices but are generally not fit for long-distance heat transport frequently encountered in various scenes. Dream pipes thus still meet our final object.

Jaegar and Kurzweg [3] and Kurzweg [4] mainly investigated high-frequency oscillations but, according to Furukawa [22], of significance are rather low- than high-frequency ones. A dream pipe designed by Kaviany and Reckker [9] ran for 0.5 Hz to 10 Hz and another one by Katsuta et al. [12] for 1, 4, 8, and 10 Hz. Hishida et al. [25] set a new device similar to dream pipe in motion for 0.5 Hz or 1.0 Hz. Operations under much lower frequencies, 0.025 Hz to 1.0 Hz, were then practiced by Hassami and Zulkifli [26]. A technical issue is now if piezoelectric drives may cause such low-frequency oscillations as well as mechanical ones [9,12,25,26]. Since early 2000s, many attempts have been made to apply piezoelectric actuators to pumps [27–29], fans [30,31], manipulators [32], agitators [33], and so on. This is along a recent trend of miniaturization of machines but all are of high frequency-oscillations. As mentioned by Park et al. [27], there exist no commercially available piezoelectric cells for low-frequency oscillations. In addition, we need those causing oscillations of larger amplitude. This is because we aim at developing a heat-pump-less heat recovery system, in which vapor compressors [34] would be replaced with dream pipes. We then noticed that Lorentz force may generate low-frequency high-amplitude oscillations without technical difficulty and recognized that electromagnetic drives are popularly used as linear motors for cryocoolers [35]. A notion of electromag-