Applied Thermal Engineering 128 (2018) 381–392

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Modelling and investigation on heat transfer deterioration during transpiration cooling with liquid coolant phase-change

Wenjie Dong [a], Jianhua Wang [a,*], Siyuan Chen [b], Bangcheng Ai [b], Xiaoguang Luo [b]

[a] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Jinzhai Road 96, Hefei 230027, PR China
[b] China Academy of Aerospace Aerodynamics, Beijing 10074, PR China

HIGHLIGHTS

- A new model describing transpiration cooling with phase change is suggested.
- Model and numerical solutions are validated by comparisons with the previous literatures.
- The heat transfer deterioration due to vapor locking pores is studied.
- Three improvements are demonstrated and compared to prevent the heat transfer deterioration.

ARTICLE INFO

Article history:
Received 10 January 2017
Revised 24 July 2017
Accepted 25 August 2017
Available online 6 September 2017

Keywords:
Transpiration cooling
Phase change
Heat transfer deterioration
Porous matrix

ABSTRACT

In this paper, a new mathematical model is suggested to describe the two-dimensional problems of the transpiration cooling with liquid coolant phase change, to simulate and analyze the effects of locally high heat flux on surface temperature and coolant flow within porous matrix. The numerical simulations indicate that the locally high heat flux significantly influences the coolant flow performances, and lead to distinct heat transfer deterioration, i.e. local vapor blocks the porous matrix, and liquid coolant flows into the region far from the superheated vapor region, which results in a higher temperature of the superheated region. Numerical analyses of different parameters reveal that the heat transfer deterioration is more serious in uniform porous matrix with a lower thermal conductivity and a larger porosity. To prevent the heat transfer deterioration, this paper demonstrates and compares the following three approaches: (1) varying local porosity and conductivity of the porous matrix; (2) using two solid walls to separate the porous matrix into three chambers; (3) varying the local thickness of the porous matrix. Using the three approaches, the maximal temperature at hot side can drop by approximately 40%, 55% and 5%, respectively. The comparisons show that the second method is more effective.

1. Introduction

Transpiration cooling is an active technique to protect thermal structures from high aerodynamic heat and force, and there have been a large number of numerical and experimental investigations on the application of transpiration cooling in aerospace field, such as the rocket nozzles [1–2], the combustion chambers of rocket engines [3–6], the first stages of gas turbine blades [7–9], the leading edges of hypersonic vehicles [10–13]. The previous investigations can be divided into two categories: using gaseous coolant or liquid coolant with phase change. Compared to transpiration cooling with gaseous coolant, the second kind of transpiration cooling is more efficient, because liquid coolant has small specific volume, and can release a larger number of phase change latent heat, which is much higher than the sensible heat.

Although a series of experimental investigations on the practical applications of transpiration cooling with phase change have been carried out by van Foreest et al. [12], Zhao and Wang [13,14], Shen and Wang [15] et al., the theoretical investigations concerned with coolant phase change problems were most limited within the numerical solutions of simplified and one-dimensional problems, for example one-dimensional steady-state heat and mass transfer in a two-phase region of a water-saturated porous medium [16], the modelling of two-phase fluid flow and heat transfer with phase change in a porous medium [17], the effects of various parameters on liquid-vapor phase change position [18], the model discussion of transpiration cooling with boiling [19], the effects of coolant injection rate and external heat flux

* Corresponding author.
E-mail addresses: dwj150mc@mail.ustc.edu.cn (W. Dong), jhwang@ustc.edu.cn (J. Wang).

http://dx.doi.org/10.1016/j.applthermaleng.2017.08.155
1359-4311/

Nomenclature

W	thickness of porous matrix, m
L	length of porous matrix, m
T	temperature, K
x, y	Cartesian coordinate, m
q	heat flux, $W \cdot m^{-2}$
m	mass flow rate per unit area, $kg \cdot m^{-2} \cdot s^{-1}$
m'	interfacial mass transfer rate, $kg \cdot m^{-3} \cdot s^{-1}$
s	liquid saturation
$\mathbf{v}$	velocity vector
$\mathbf{v}'$	superficial or Darcian velocity vector
u, v	velocity components along x and y axes, m/s
p	pressure, Pa
$\mathbf{g}$	gravity vector
K	permeability, m^2
H	specific enthalpy, $J \cdot kg^{-1}$
H_{lv}	latent heat of evaporation, $J \cdot kg^{-1}$
R_g	gas constant, $J \cdot kg^{-1} \cdot K^{-1}$
h	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
k	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
d_p	particle diameter, m
c_p	specific heat, $J \cdot kg^{-1} \cdot K^{-1}$

Greek symbols

ρ	density, $kg \cdot m^{-3}$
ε	porosity
μ	dynamic viscosity, $N \cdot s \cdot m^{-2}$

Subscripts

c	coolant
l, v	liquid, vapor
i, f	fluid in different region
s	solid
0	reference
eff	effective
sat	saturated state

on distributions of temperature, pressure and velocity [20], the critical heat flux and coolant mass flow injection [21], the effects of heat-flux direction on heat and mass transfer behaviors [22], the capturing of the interfaces of single- and two-phase regions [23], the comparison of evaporation processes in porous media during transpiration cooling with two models [24], the effect of variation of heat input, inlet temperature, inlet mass flux and fraction of components in transpiration cooling process [25], and the numerical analysis of phase change transpiration cooling with a modified model [26]. However, in these one-dimensional problems, boundary conditions and characteristic parameters of the porous matrix used were assumed to be uniform and constant.

In the practical applications of aerospace field, transpiration cooling may meet quite complicate conditions: local thermal load and shock. Liu et al. [27] pointed that a local thermal shock can lead to local heat transfer deterioration, because gaseous coolant may circumvent local superheated area and flow to the areas with relatively lower temperature, then the superheated area expands, and until local ablation occurs. Compared to gaseous coolant, liquid coolant during transpiration cooling process is less stable due to evaporating within pores, and the heat transfer deterioration phenomena are more serious. Therefore, it is necessary to study the two-dimensional transpiration cooling problems with liquid coolant phase change, discuss the phenomena of heat transfer deterioration, and search for effective improvement approaches.

2. Physical model

The physical model used in this work is shown in Fig. 1. A porous matrix with a length of $L = 0.08$ m and a thickness of $W = 0.02$ m is located horizontally, and its hot surface is exposed to a local thermal shock, a higher heat flux q_1 is loaded in the middle of the matrix $l_1 = 0.25$ L, and a lower heat flux $q_2 = 1 \times 10^6$ W/m^2 is loaded in the other area. The q_1/q_2 ratio varies from 2 to 4.5. Liquid coolant at a temperature of T_c is injected from opposite direction into pores with a mass flow rate of m. The left and right vertical boundaries are assumed to be impermeable and thermally insulated.

2.1. A new mathematical model

Our model is based on the following two assumptions, which are commonly used in [20–22]:

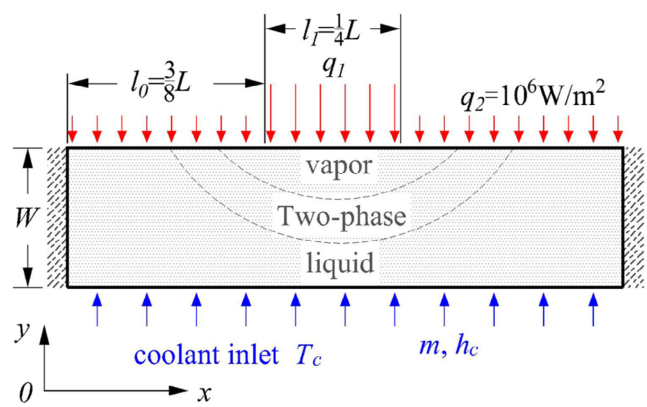

Fig. 1. Physical model.

(1) Fluid flow and heat transfer are in steady state
(2) Coolant in liquid state is incompressible while in vapor state is regarded as ideal gas

In the previous theoretical and numerical investigations on transpiration cooling with coolant phase change, Separate Phase Model (SPM) was used in [20–23]. SPM can clearly describe the fluid flow and heat transfer performances in single and two- phase regions, but using this model it is difficult to solve two or three-dimensional problems due to the troubles of tracking the interfaces of phase change. The energy conservation equations of fluid in SPM [20] are described as follows:

In single phase region:

$$\nabla \cdot (\rho_i \varepsilon \mathbf{v}_i H_i) = \nabla \cdot (\varepsilon k_i \nabla T_i) + q_{sf} \quad i = (l)\ liquid,\ (v)\ vapor \tag{1}$$

In two-phase region:

$$\nabla \cdot [\rho_l \varepsilon s \mathbf{v}_l H_l + \rho_v \varepsilon (1-s) \mathbf{v}_v H_v] = \nabla \cdot (k_{f.eff} \nabla T_f) + q_{sf} \tag{2}$$

where ε, s, ρ, $\mathbf{v}$, k, T and H represent porosity, saturation, density, velocity, thermal conductivity, temperature and specific enthalpy, receptivity. Subscript "i" represents single liquid phase "l" and single vapor "v". Other variables q_{sf} and $k_{f.eff}$ represent convective heat flow of fluid-to-solid and effective thermal conductivity, respectively.