International Journal of Heat and Mass Transfer 127 (2018) 658–676

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Simulation of motion, deformation, break-up and deposition of copper droplets transported in internal compressible flow including phase change effects

L.A. Florio

US Army ARDEC, Technology Branch, Small Caliber Armaments Division, Picatinny Arsenal, NJ 07806, United States

ARTICLE INFO

Article history:
Received 29 May 2018
Received in revised form 5 August 2018
Accepted 14 August 2018

Keywords:
Molten copper
VOF
CFD
Droplet deformation
Droplet solidification
Compressible flow

ABSTRACT

In this work, the motion, deformation, break-up, and deposition of molten copper droplets transported by high speed, high pressure, and high temperature gas flow along a steel internal flow path are examined numerically using a volume of fluid based approach. The study of the related phenomena is motivated by the erosion and fouling patterns along flow paths caused by such droplets. Good correlation to literature was achieved for a single drop impact. Methods were applied to multiple drops moving with gas flow in a main flow channel with a by-pass with the strength of the flow varied by changing the initial pressure in the main channel gas by up to a factor of four. The amount of copper removed from the main flow path grows from 58% to 87% when the driving pressure is quadrupled. A greater portion of the copper in the by-pass section is solidified as well with 90% solidified for the higher pressure, compared to 60% at the lower pressure. Solidification of the copper and melting of the steel require the proper combination of the molten copper location, the temperatures in the copper, steel, and gas, and the velocity of the transporting gas flow. The knowledge gained from the study can be applied to mitigate the fouling and erosion that may develop along internal surfaces. Because of the need for a small element size to prevent copper mass loss, the use of this method with complex three dimensional geometries may be limited.

Published by Elsevier Ltd.

1. Introduction

This work involves the numerical investigation of the characteristics of the transport, deformation, break-up, and deposition of molten copper droplets, carried by higher temperature, pressure, and velocity air flow in an internal flow path with a by-pass junction from the main flow path, and the changes in these characteristics with the strength of the driving flow conditions. Solidification of the droplets and the melting of the steel flow path material are considered.

The deposition of metallic droplets impinging on a surface substrate is a phenomena of importance in many manufacturing processes [1] and in internal flows where metal droplets are transported with the flow. Common processes related to molten metal motion and surface accretion include spray casting [2], coating application, thermal spraying, spray atomization [3] and fouling and erosion along internal flow paths. Complex, interdependent thermal and mechanical phenomena develop during the interaction of the droplets with the transporting fluid and the interaction of the droplets with substrate surfaces including the droplet "splat" formation and solidification and melting of the droplet and substrate. Better control of such processes can be achieved through an improved understanding of the attributes of the droplet deformation, break up, and transport, the regions along the flow path most prone to build up or erosion of the metal material, and the positions where molten substrate/flow-path material may be wiped away by the flow. Such information may be revealed through the use of physics based computational simulations.

In the current work, the motion of copper droplets carried by high speed, pressure, and temperature air flowing within an internal flow path for a range of flow driving conditions is analyzed through computational fluid dynamics based simulations. The system studied includes a main flow channel with a by-pass flow path leading to a secondary flow path and a slug moving along the main flow path. This slug assists in diverting flow into this secondary flow path (see Fig. 1). The flow conditions are examined to determine the amount of copper material that moves through various flow paths and the level of build-up on the solid surfaces, along with information on how much of the copper is solidified and any flow path melting. The initial driving pressure in the main flow channel is varied to investigate the influence of the strength of the

E-mail address: laurie.a.florio.civ@mail.mil

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.059
0017-9310/Published by Elsevier Ltd.

Nomenclature

Vectors

- **F** surface tension force per unit volume (N/m^3) (13)
- **I** identity matrix (12)
- **n** volume fraction gradient (12)
- $\hat{\mathbf{n}}$ unit volume fraction gradient (12)
- **Θ** interface surface stress (N/m) (12)
- **V** fluid velocity (m/s) (1)
- **X** coordinate directions (1)–(7)

Scalars

- A_{mush} Mushy zone parameter (9)
- *C, G, Y* turbulence parameters as defined in [20] (7a), (7b)
- *F* volumetric surface tension force (N/m^3) (5),(13)
- *h* fluid sensible enthalpy (J/kg-K) (6)
- *H* fluid enthalpy (J/kg-K) (6)
- ΔH latent heat content (J/kg-K) (11a)
- *k* thermal conductivity (W/m-K) (6)
- *L* latent heat (J/kg-K) (11a)
- $\dot{m}$ volumetric mass transfer rate (kg/s-m^3) (1)
- *p* pressure (N/m^2) (5)
- *S* volumetric source terms ($S_{\alpha q}$, $\mathbf{S_m}$, S_e, S_κ, S_ε) (1),(4)–(7), (9)–(11)
- *T* temperature (K) (3)
- T_L liquidus temperature (K) (8)
- T_S solidus temperature (K) (8)
- *t* time (s)

Greek

- α volume fraction (1),(2)
- β liquid fraction (8)
- ϵ_{mush} correction to prevent division by zero (9), (10)
- κ,ε turbulence parameters (7a), (7b)
- ρ density (kg/m^3) (6)
- τ fluid stress tensor (N/m^2) [19] (6)
- $\sigma_{\varepsilon\ or\ \kappa}$ turbulence parameters [20] (7)
- σ surface tension coefficient (N/m) (12)
- μ viscosity/turbulent viscosity (kg/m-s) (7a), (7b)

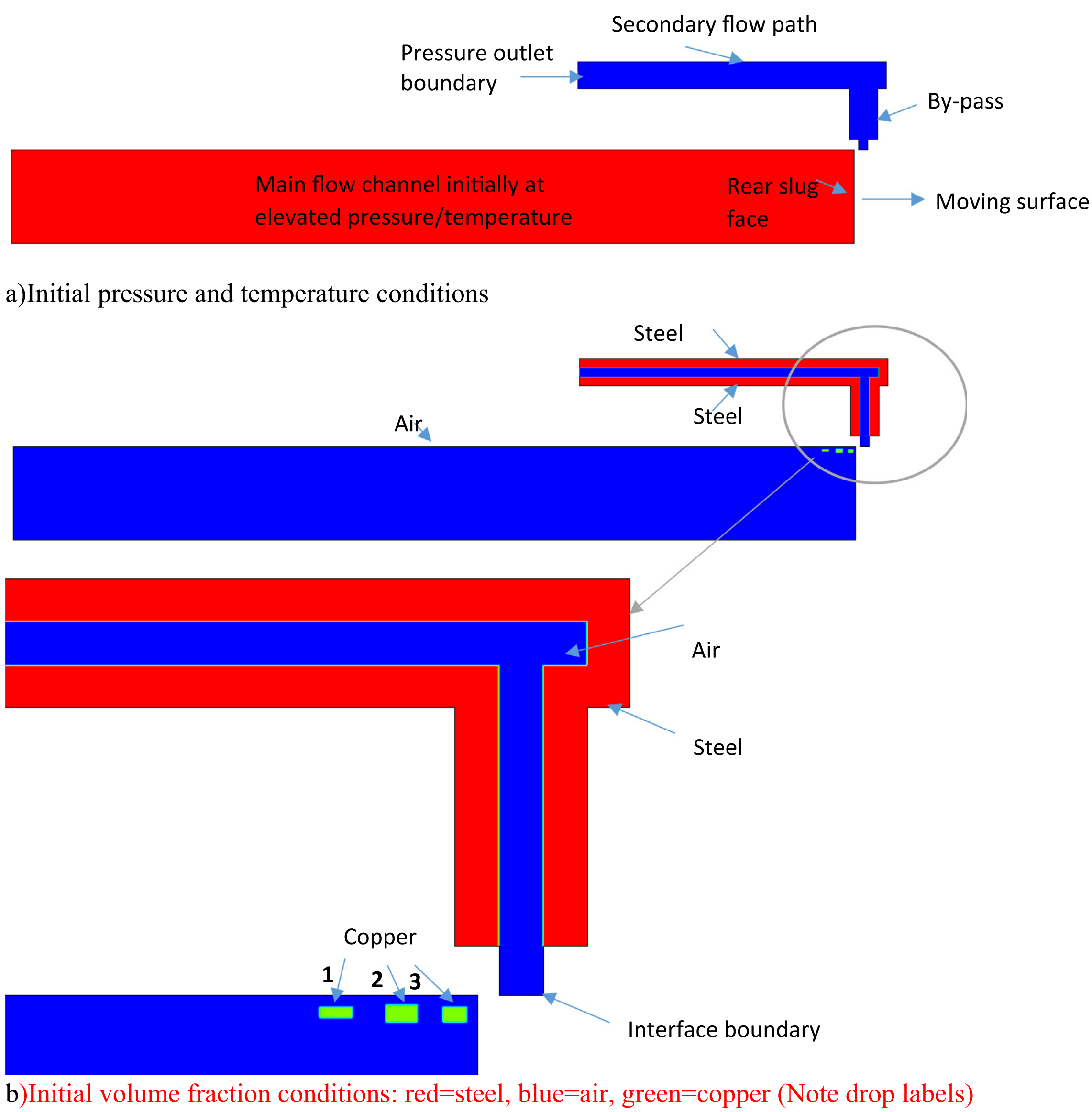

Fig. 1. System configuration and initial conditions to study copper droplet motion.