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Infiltration of a porous matrix by a solidifying liquid metal: A local model

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ABSTRACT

This paper describes the first step of a study dedicated to the development of a macroscopic model of casting of a metal foam by infiltration and solidification of a liquid metal in a porous mould. The first stage presented here describes a local model of injection of the metallic melt in a capillary tube and subsequent solidification of the metal by heat transfer to the duct walls.

The model is intended to account for the air/liquid interface displacement during the infiltration phase, for the heat transfer to the wall and for the growth of the solid phase in the presence of the fluid flow. The objective is to determine the influence of the operating conditions on the penetration depth and on the solidification time in a simplified geometry before using this local information in a macroscopic homogenized model presently under development.

1. Introduction

The motivation of the present study is the elaboration of metallic foams. A metal foam is a porous structure whose solid matrix has a large fraction of cells (Fig. 1), interconnected or not, and may be used in a variety of applications: open-cell foams are used in heat exchangers to increase heat transfer, while closed-cell foams may be employed as impact-absorbing material such as in vehicle's crash box. Metal foams present promising qualities since they retain the high mechanical or thermal properties of the metal while reducing the weight up to 90%. Many different manufacturing processes may be used for their elaboration, such as the injection of gas into a liquid or the use of blowing agents, but these techniques fail to satisfy important requirements, mainly the necessity to control the structure of the foam, its homogeneity and its effective properties.

The CTIF [4]*[1] proposed the casting process CastFoam® for metal foams manufacturing which produces well defined homogenous foams, making use in particular of Kelvin cells to elaborate perfectly regular foams. It consists in injecting a liquid metal into a porous mould consisting of a regular arrangement of sand or salt beads which are destroyed after solidification of the metallic structure (Fig. 2). The competitiveness of the metal industry concerned with the elaboration of such products results of severe specifications intended to reduce the cost of the manufacturing process. Therefore there is a need for optimizing this process before it can be employed in the metal transformation industry.

In the frame of the modelling approach of the complete process of infiltration of the porous matrix by a liquid metal and its subsequent solidification, it is first relevant to study the heat transfer mechanisms involved at the local scale of a pore, namely the solidification process of a liquid flowing in a capillary tube. The bibliographical review reveals that a huge corpus of publications exists on this topic. Mainly two viewpoints are concerned with such studies:

- on the one hand, metallurgists are interested by determining the “fluidity” of metals in capillaries. The development of fluidity tests has been particularly active in the 60s and 70s, - on the other hand, the community of heat transfer and fluid mechanics has for a long time been concerned by the coupling between solid-liquid phase change and convection in the fluid phase, and in particular by freezing of a fluid flow in ducts.

We will review the main studies in both domains and then try to locate our contribution in this field.

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[1] The symbol * sends to the reference list for the URL of the websites.

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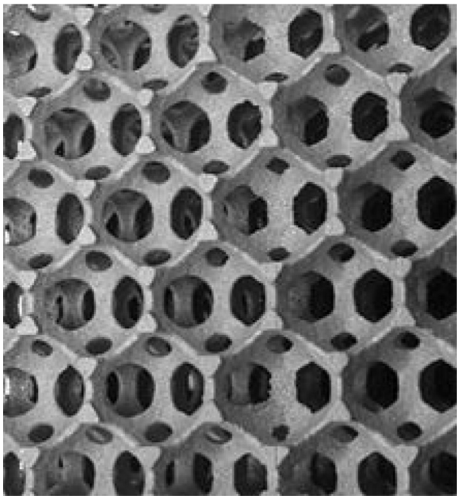

Fig. 1. Detail of a periodic metal foam.

Fig. 2. The sand mould before infiltration by the liquid metal.

1.1. Metallurgy studies on the fluidity of metals in casting

In metallurgy, the efficiency of a number of casting processes such as mould filling depend on the ability of liquid metals or alloys to fill the mould cavity before the metal completely freezes (see Ref. [17]. Early phenomenological observations have been performed [19,21] and led to the characterization of solidification modes both for pure metals and binary alloys. For this purpose the concept of “fluidity” has been defined: many experimental tests have been realized consisting in pouring liquid metal by gravity in pyrex tubes or other more elaborated devices and measuring the length of the tube filled with metal when solidification has blocked the fluid flow. The fluidity is the distance in millimeters reached by the metal. Obviously, this parameter depends on the metal properties (latent heat, viscosity, etc.), but it is also largely resulting from the operational conditions of the test (initial liquid temperature, mould nature, shape and temperature, etc.). The extreme dispersion of the results for a given metal or alloy is thus not a surprise, and the observations have led in general to qualitative trends and conclusions, as shown in the reviews by Ref. [1] or [24]. However relatively few attempts to model the infiltration and solidification process in a porous mould have been proposed (see e.g. Ref. [12].

1.2. Heat transfer studies on solidification of liquids flowing inside ducts

Many studies have been motivated by the great number of applications involving heat transfer with liquid-solid phase change (solidification) of a liquid flowing in a duct. Casting of metals, food processing, freezing of water in pipes or by extension to the deposition of particles on duct walls by molecular diffusion such as in the formation of constrictions in blood vessels or the deposition of paraffin on the inner walls of pipelines in deepwater offshore petroleum extraction [18] are examples of such situations of the interaction of a fluid flow with a change of a duct morphology.

In most situations, the objective is to predict the increase of the pressure drop due to the decreasing flow section, and the transient character of the mechanism is crucial, since the time evolution of the system finally may lead to the blockage of the fluid flow in the tube. Given the large number of industrial applications, there is an impressive corpus of scientific publications on the problem of solidification of liquids flowing inside ducts, mainly published in the decades of the 70s and 80s. The bibliography is summarized in several reviews [2,5,7,33]. The review by Weigand et al. is specifically dedicated to freezing processes with forced convection inside ducts, while the papers by Cheung and Epstein review the studies concerning solidification or melting in external or internal flows, inclusively by natural convection. The viewpoint presented by Fukusako and Yamada is to separately analyze the process of solidification in ducts or around cooled bodies of flowing liquids for pure substances and for binary systems. If we refer to the topic of the present study – namely solidification of an internal forced flow in a duct – the quasi totality of the published works reported in these reviews are concerned with an established flow in a tube with an imposed inlet velocity profile, the temperature of the wall tube being suddenly decreased below the freezing temperature of the fluid.

The solid crust formed at the duct wall creates a constriction of the flow, increasing the pressure drop in the pipe until a steady state is reached or obstruction of the duct. Following the early work reported in [35], most investigations in this domain are interested in calculating the evolution of the pressure drop during the solidification process and in characterizing the influence of natural convection and the three-dimensional effects it may create. The configuration under study generally consists of a steady, fully developed laminar flow in a rectangular or circular duct whose external wall is suddenly cooled on a given length by imposing a temperature lower than the freezing point of the fluid or extracting a constant heat flux (Fig. 3). A steady state situation is generally obtained where the thickness of the frozen crust does not evolve in time and the fluid flows in the constricted channel (no flow blockage). Since the mass flow rate is kept constant, the velocity locally increases when the duct diameter gets smaller and the stability of the solid-liquid interface may be affected: the smooth interface observed in the laminar regime may evolve towards a wavy interface corresponding to local changes in the heat transfer due to changes in the flow regime (see e.g. [8]). It must be emphasized that a very broad majority of studies aiming at modelling the problem do not consider the infiltration problem, except for some applications concerned with “cold filling” of pipes [15,16]. Concerning the boundary conditions, almost all the studies consider an imposed established velocity profile at the tube inlet [3,31] and the thermal boundary conditions are always first or more