Nigerian Research Journal of Engineering and Environmental Sciences 2(2) 2017 pp. 524-529

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

DETERMINATION OF THE COMPRESSIBILITY OF AIR IN CASTING MOULD

***Inegbedion, F. and Akpobi, J.A.**

Department of Production Engineering, Faculty of Engineering, University of Benin, Benin City, Nigeria.
*francis.inegbedion@uniben.edu

ARTICLE INFORMATION

Article history:
Received 20 October, 2017
Revised 08 November, 2017
Accepted 15 November, 2017
Available online 29 December, 2017

Keywords:
Compressibility
Continuity equation
Control volume
Equation of state
Mach number

ABSTRACT

The air in the mould during casting is displaced by the liquid metal in a very rapid manner necessitating the need to account for its compressibility. This work has established the compressibility of air in casting mould by using the continuity equation of a controlled volume and the equation of state. From the prediction of air molecule speed using the kinetic energy formula and comparing with the local speed of sound (Mach number), it was established that the Mach number was greater than 1 which shows that the air flow in the casting mould was compressible. Comparing further with experimental results shows that the air in the mould cavity is compressible as it is displaced by the liquid metal filling the cavity.

1. INTRODUCTION

Casting is a manufacturing process for making complex shapes of metal materials. There are two main stages – filling process and solidification process – in casting production. In the filling process the gating system composed of pouring cup, runner, sprue, sprue-well and ingate, is designed to guide liquid metal into the mould cavity for filling (Feng, 2008). In the solidification process the riser system is used to compensate for shrinkage caused by casting solidification (Feng, 2008).

A riser or a feeder is a reservoir built into the casting mould to prevent cavities due to shrinkage (Lagdive and Inamdar, 2013). Apart from serving as a reservoir to compensate for shrinkage during solidification, the riser also serve as a channel through which the air displaced as a result of filling the mould cavity with the molten metal goes out of the mould cavity.

For manufacturing engineers there are many situations where compressible flow understanding is essential for adequate design. These processes include situations not expected to have a compressible flow, such as casting and injection moulding (Meir, 2013). Casting is a process in which liquid metal, mostly aluminium, is injected into a mould to obtain a near final shape. The air is displaced by the liquid metal in a very rapid manner, in a matter of milliseconds; therefore its compressibility has to be taken into account (Meir, 2013).

A fluid is said to be incompressible if the volume change is zero ($\nabla \bullet v = 0$) and compressible if the volume change is not zero ($\nabla \bullet v \neq 0$) (Reddy, 1993; Reddy 2006). The compressibility of a fluid is, basically, a measure of the change in density that will be produced in the fluid by a specific change in pressure and temperature (Meir, 2013).

Porosity is the most persistent and common complaint of casting users. Porosity in casting contributes directly to customer's concern about reliability and quality (Monroe, 2005). To control porosity an understanding of its source and causes is essential. Porosity in casting is due to air bubbles being trapped during mould filling and solidification (Monroe, 2005). One source of porosity in casting is a failure to eliminate all the air in the Mould Cavity during mould filling (Scott and Goodman, 1978). Aqida et al. (2004) examined the effects of porosity on mechanical properties of metal matrix composite and observed that porosity tends to decrease the mechanical properties of metal composite. Peti and Grama, (2011) described porosity as trapped air in the casting which can come from several sources. Much work has been done to characterize the factors that causes porosity in casting, and to analyze the impact of porosity on the mechanical properties of metals (Aqida et. al., 2004). What has not yet been done is the behaviour of air (the main cause of porosity) in casting mould. The aim of this work therefore was to determine the compressibility of air in casting mould as liquid metal is poured is fill the mould cavity.

2. METHODOLOGY

2.1. Compressibility of Air in Casting Mould

The continuity equation of a control volume was used to determine the compressibility of air in casting mould. The continuity equation is obtained by applying the principle of conservation of mass to flow through a control volume (Meir, 2013)

$$\dot{m}_1 = \dot{m}_2 \tag{1}$$

$$\dot{m} = \rho U A \tag{2}$$

$$\rho_1 U_1 A_1 = \rho_0 U_0 A_0 \tag{3}$$

$$\therefore \frac{U_1}{U_0} = \frac{\rho_0 d_0^2}{\rho_1 d_1^2} \tag{4}$$

From the ideal gas equation of state we get

$$P = \rho R T \tag{5}$$

$$\rho_1 = \frac{P_1}{R T_1} \ \& \ \rho_0 = \frac{P_0}{R T_0} \tag{6}$$

According to Charles law

$$\frac{V}{T} = C \tag{7}$$

$$\therefore P_1 = P_0 = P_{atm} \tag{8}$$

Where m is Mass flow rate, ρ the density of air at 0°C = 1.293 kg/m^3, U = Velocity, A = Area, P_{atm} is Atmospheric Air Pressure 101,325N/m^2, R the Gas Constant for Air = 287.045 J/kg.K, T_1 the Melting Point of Aluminium = 660^{0}C + 273.15 = 933.15K, T_0 the Ambient Temperature = 34^{0}C + 273.15 = 307.15K, T the Absolute Temperature, V the Volume, C = Constant, d_0 is the diameter of the riser at the top and d_1 is the diameter of the riser at the bottom.

From Equation (8):

$$P_1 = P_0 = P_{atm} = 101325 \quad \text{N/m}^2 = 0.101325 \quad \text{N/mm}^2 \tag{9}$$

From Equation (6):

$$\rho_1 = \frac{P_1}{RT_1} = \frac{101325}{287.045 \times 933.15} = 0.3783 kg/m^3 = 3.783 \times 10^{-10} kg/mm^3 \tag{10}$$

$$\rho_0 = \frac{P_0}{RT_0} = \frac{101325}{287.045 \times 307.15} = 1.1493 kg/m^3 = 1.1493 \times 10^{-9} kg/mm^3 \tag{11}$$

Substituting ρ_1 and ρ_0 into Equation (4), we obtain:

$$\frac{U_1}{U_0} = 3.0379 \frac{d_0^2}{d_1^2} \tag{12}$$

Case 1

For a cylindrical riser $d_1 = d_0$ therefore, $d_1/d_0 = 1$, for any given value, thus Equation (12) becomes

$$U_1 = 3.0379 U_o \tag{13}$$

Case 2

For a tapered riser, Feng, (2008), optimized the taper angle as 25° and the taper height as 30mm. Behera et al. (2011) validated the following parameters as the optimized parameters for risers, Height, H = 82mm, Riser diameters d_1, = 40.70mm, d_o = 55mm

Substituting these values into Equation (12)

$$U_1 = 5.5477 U_o \tag{14}$$

Case 3

For a bottle riser using same parameters as in taper risers

$$U_1 = 1.6636 U_o \tag{15}$$

U_o represents initial velocity of air within the casting mould

U_i represents the velocity of air as it leaves the casting mould through the riser

2.2. Prediction of Air Molecule Speed

All gas particles have kinetic energy due to their motions. Temperature is a measure of this microscopic kinetic energy. Maxwell and Boltzmann deduced that the mean kinetic energy is proportional to temperature (Leonard, 1984). This statement is usually written mathematically as:

$$KE_{avg} = \frac{3}{2}kT \quad \text{and} \qquad \frac{1}{2}mv^2 = \frac{3}{2}kT \tag{16}$$

$$v = \sqrt{\frac{3kT}{m}} = 522.9365mm/s \tag{17}$$

where, k is the Boltzmann constant = 1.38 × 10^{-23} (J/K), m the particle mass = 4.65 x 10^{-26} kg, v the velocity of air at 34^0C and T the temperature in Kelvin = 34 ºC + 273.15 = 307.15 K

Let $U_0 = v$ ` (18)

For case 1:

$$U_1 = 1588.6288mm/s \tag{19a}$$

For case 2:

$$U_1 = 2901.0948mm/s \tag{19b}$$

For case 3:

$$U_1 = 869.9572mm/s \tag{19c}$$

3. EFFECTIVE INCOMPRESSIBILITY

In steady flow, a fluid is incompressible when the flow speed is less than the local speed of sound. The ration of the local flow speed U and the local sound speed C is called the (local) Mach number (Childress, 2008; Fitzpatrick, 2014).

$$Ma = \frac{U_1}{C_{air}} \tag{20}$$

In terms of the Mach number, flow is compressible if the local Mach number, Ma ≥ 1 (Childress, 2008). The expression for the speed of sound in air is:

$$C_{air} = \sqrt{\frac{\gamma P}{\rho}} \tag{21}$$

Where C_{air} is speed of sound in air, P the atmospheric air pressure 101,325 N/m^2 = 0.101325 N/mm^2 and ρ the density of air at 0^0C = 1.293 kg/m^3 = 1.293×10^{-9} kg/mm^3

$$C_0 = \sqrt{\frac{1.402P}{\rho}} = 331.4615mm/s \tag{22}$$

The equation of state of an ideal gas is

$$PV=RT \tag{23}$$

The definition of density is:

$$\rho = \frac{M}{V} \tag{24}$$

Substituting Equations (23) and (24) into (22) results in:

$$C_0 = \sqrt{\frac{1.402RT}{M}} \tag{25}$$

where R is the universal gas constant, T the absolute temperature, and M the mean molecular weight of the gas at sea level. Since R and M are constants, the speed of sound may be shown to have a first-order dependence on temperature as follows:

$$C_0 = \sqrt{\frac{T}{273}} \tag{26}$$

The speed of sound is seen to increase with the square root of the absolute temperature. Substituting Celsius conversion factors and the reference speed of sound into Equation (26) yields:

$$C_{air} = 331.4615\sqrt{1 + \frac{t}{273.15}} \tag{27}$$

where t is the temperature in degrees Celsius

With Equation (27), the speed of sound in air can be computed for any temperature. The speed of sound at 660 ^{o}C (i.e. melting point of aluminium) is thus:

$$C_{660} = 612.6640 mm/s \tag{28}$$

From Equation (20), the Mach number for the three cases mentioned can thus be computed.

Case 1: Ma=2.5916
Case 2: Ma=4.7326
Case 3: Ma=1.4192

4. RESULTS AND DISCUSSION

From the continuity equation of a controlled volume and the equation of state, a volume change was established as indicated by Equations (10) and (11) which shows that a change in density of air in the casting mould occurred. This change in density shows that there was a decrease in volume indicating (compressibility). This agrees with the findings of Reddy (1993), and Reddy (2006). From the prediction of air molecule speed using the kinetic energy formula and comparing with the local speed of sound (Mach number) (Equation (20)) it was observed that the Mach number was greater than 1 indicating that the air flow in the casting mould was compressible.

5. CONCLUSION

In this work, the compressibility of air flow in the casting mould was established by applying the principle of conservation of mass to flow through a control volume, the gas laws and the equation of state for an ideal gas. The kinetic energy formula was used to determine the air molecular speed, the local speed of sound was also determined and the compressibility of air in the casting mould was established using the local Mach number (C). The results were compared with experimental results obtained from the measurement of the velocity from the riser outlet using a rotary vane anemometer..

6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Aqida, S. N., Ghazali, M. I. and Hashim, J. (2004). Effects of porosity on mechanical properties of metal matrix composite: An overview. *Jurnal Teknologi*, *40*(A), 17-32.

Behera, R., Kayal, S. and Sutradhar, G. (2011). Solidification behavior and detection of Hotspots in Aluminium Alloy castings: Computer Aided Analysis and experimental validation. *International journal of applied engineering research*, *1*(4), pp 715-726

Childress, S. (2008). *An Introduction to Theoretical Fluid Dynamics*, Cambridge University Press; pp. 160 – 163

Feng, L. (2008). *Optimized Design of Gating/Riser System in Casting Based on CAD and Simulation Technology*. MSc Thesis, Worchester Polytechnic Institute.

Fitzpatrick, R. (2014). *Theoretical Fluid Mechanics*. CRC; pp. 415

Lagdive, P. B. and Inamdar, K. H. (2013). Optimization of riser in casting using genetic algorithm. *International Archive of Applied Sciences and Technology*, *4*(2), pp. 21-26.

Leonard B. L. (1984). *The Kinetic Theory of Gases*, 2 Ed., fifth impression, McGraw Book Company, Inc. New York and London p. 28.

Meir, G. B. (2013). Basics of Fluid Mechanics. *March, Orange Grove Books*, Chicago, Il.

Monroe, R. (2005). *Porosity in Castings.* AFS Transactions. American foundry Society, Schaumburg, IL USA.

Peti, F. and Grama, L. (2011). *Analyze of the Possible causes of Porosity Type Defects in Aluminium High Pressure Diecast Parts*. Scientific Bulletin of the Petru Maior, University of Targu Mures

Reddy, J. N. (1993). *An Introduction to the Finite Element Method*, Second Edition, McGraw-Hill Inc., pp 117 – 123; 482 – 503; 598 – 599.

Reddy, J. N. (2006). *An Introduction to the Finite Element Method*, Third Edition, International Edition McGraw-Hill Inc. pp. 146 – 147.

Scott, W. D. and Goodman, P. (1979). Gas Generation at the Mold/Metal Interface. *1978 AFS Research Reports*, pp. 63-76.