Characterizing Flow Losses Occurring in Air Vents and Ejector Pins in High Pressure Die Castings

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ABSTRACT

It will be demonstrated how the commercial computational fluid dynamics (CFD) software, ***FLOW-3D®***, can be used to model the flow losses occurring in ejector pins and air vents in high pressure die castings. The results from an ejection experiment done without melt at a commercial tool shop will be discussed. These results will then be used to compute flow loss coefficients for the air vents, ejector pins and residual leaks with the help of the adiabatic bubble model in ***FLOW-3D®***. We will explore an effective tool for calibrating the losses that occur during a pressurized fill in high pressure die castings.

INTRODUCTION

Surface defects reduce thermal and mechanical properties such as yield strength, ductility and modulus of elasticity of parts produced in high pressure die casting. The surface defects occur due to air entrapment and/or solidification shrinkage. Entrapped gases during fill and the gases evolved during decomposition of lubricants, cause porosity. Vacuum die casting can eliminate these gases. Vacuum valves are expensive and there is a possibility of destroying the valve and/or pump if the valve is not closed before the metal leaves the shot sleeve. Moreover, an additional runner system needs to be adequately designed so that effective cooling and solidification occurs preventing the metal from entering the vacuum valve. If no vacuum is used then adequate venting along with proper gating and runner design can eliminate gas porosity. Venting helps eliminate entrapped air by allowing the gas to have an outlet during the fill. Venting is the easiest and least expensive method to use. The amount of venting through the sleeve, ejector pins, parting line, and vacuum valves are considered while designing vents.

This paper discusses air flow losses through orifices, the methodology used to analyze these losses, CFD software used, experimental set-up, and a discussion of the results.

FLOW THROUGH ORIFICES

The flow of gases through various components in a die is similar to the flow of gases in a pipe. The pressure drop of gases in a pipe include

1. Pressure losses due to expansions or contractions of area
2. Losses due to geometry-entrance and exits of the pipes, open or partially closed valves, tees, bends, or other fittings
3. Moody type friction loss

For the first two types of pressure losses, the flow can be complex making the theory weak. For the first two losses, it is challenging to characterize the loss coefficients due to the complexity of the flow. As a result experimental data must be relied upon. There is a greater reliance on experiments. All measured losses can be associated with a loss coefficient which relates the head loss to the velocity of the flow. The loss coefficient is calculated using Eq. 1[1]:

$$K = \frac{h}{V^2/2g} = \frac{\Delta p}{1/2\,\rho V^2} \qquad (1)$$

Where:
K is the loss coefficient which is dimensionless
V is velocity in units of length/time
g is gravity in units of length/time^2
Δp is the pressure drop in units of force/area
ρ is the density in units of mass/volume
h is the head loss in units of length

A less desirable way to calculate these losses would be to use the Darcy friction-factor relation. This uses an equivalent length and the Moody friction diagram to account for these losses. The loss is related to velocity by Eq. 2[1].

$$h = f\frac{L_{eq}}{d}\frac{V^2}{2g} = K\frac{V^2}{2g} \qquad (2)$$

Where:
f is the Darcy friction factor which is dimensionless
L_{eq} is the equivalent length of pipe in units of length
d is the diameter or hydraulic diameter in units of length
V is velocity in units of length/time
g is gravity in units of length/time^2
K is the loss coefficient which is dimensionless

For an incompressible, steady flow, the pressure change can be estimated using the continuity equation and Bernoulli's equation. From these equations, the following volumetric flow rate can be derived[2]:

$$Q = C_d A Y \sqrt{\frac{2\Delta p}{\rho}} \qquad (3)$$

Where:
Q is the volumetric flow rate in units of volume/second
A is the area of the restriction in units of length^2
C_d is the discharge coefficient which is dimensionless
Δp is the pressure drop in units of force/area
ρ is the density in units of mass/volume
Y is the compressibility factor for gas

This method is available in ***FLOW-3D®*** for modeling valves and will be used in this paper.

METHODOLOGY EMPLOYED IN THIS PAPER

In this paper the commercial casting simulation software ***FLOW-3D®*** was used to simulate the flow losses occurring in a die used for high pressure die castings. Flow losses at a valve, ejector pins and those due to residual leaks were analyzed. An end head of a motor was used as the representative part for this study. Injection experiments without melt were performed at the Littler DieCast in Albany, Indiana. The die was connected to a vacuum valve without the vacuum pump, so that the valve acted like a vent. These experiments were done under the following conditions, namely as follows: all open, all closed, vacuum valve closed, parting line closed, and ejector pins and parting line closed.

One of the ejector pins was replaced with the pressure transducer to monitor the pressure inside the part as a function of time for each of these runs. The experimental data showed that the primary flow losses were due to the valve, the ejector pins, and residual leaks.

Simulations were run with ***FLOW-3D®*** to calibrate these losses with the help of the valve model present in the code. This was done by comparing the data from ***FLOW-3D®*** with experiments in order to validate the code and then determining the cumulative loss coefficients for the flow losses.

FLOW-3D®: A DESCRIPTION

The Volume of Fluid method (VOF) is an algorithm used for accurately tracking a sharp interface between two fluids. In casting problems, this can be the interface between the moving metal and the vacuum or air present in the mold or die. The original Volume of Fluid method was first introduced by Hirt and Nichols[3]. The most important element in the standard VOF method is the fluid fraction (denoted as F). F represents the fluid fraction occupied by the metal/alloy in a control volume and has values between 0 and 1. The VOF method determines the exact location and orientation of the moving metal front in a given computational cell based on the values of the fluid fraction in the cell and its neighboring cells.

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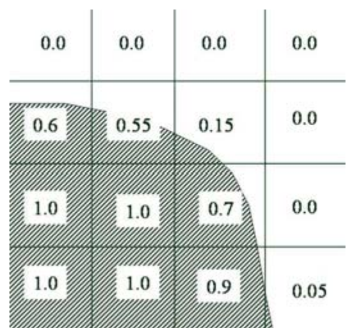


Figure 1: Typical values of the VOF function near a moving metal front.

Figure 1 shows typical values of the VOF function (F) near a moving metal front. The standard VOF method advects this front based on the existing velocity field. This is done by solving the kinematic equation for the VOF function. In the absence of any mass sources this is given by Eq. 4.

$$V_f \frac{\partial F}{\partial t} + \nabla(AUF) = 0 \qquad (4)$$

Where:
$A = (A_x, A_y, A_z)$ is the area vector for the moving front
V_f is the VOF function for the metal/alloy
U is the velocity vector (u, v, w)
AU is the vector $(A_x u, A_y v, A_z w)$

FLOW-3D® uses an advanced VOF method with several enhancements[4] over the standard VOF method. This enhanced method, TruVOF® is used to accurately track the moving metal front during a filling simulation for the cast part. ***FLOW-3D®*** is a 3D-transient Navier-Stokes solver.

The valve model[4] in ***FLOW-3D®*** allows the user to model vents present in the die. The valve can be placed at any location in the die. The flow through the valve is described by Eq. 3, where C_d accounts for frictional losses and Y takes the compressibility of the gases into account. A cumulative loss coefficient is defined by[4] Eq. 5.

$$K = \frac{A\, C_d\, Y}{\sqrt{\rho}} \qquad (5)$$

The valve model in ***FLOW-3D®*** is used in conjunction with the adiabatic bubble model which represents the air present in the die as an adiabatic bubble. The pressure in the die is computed according to:

$$PV^{\gamma} = constant \tag{6}$$

Where
P is the pressure in the bubble
V is the volume of the bubble
γ is the ratio of specific heat capacity at constant pressure to that at constant volume

INJECTION EXPERIMENTS WITHOUT MELT

Injection experiments without melt were performed at Litter DieCast in Albany, Indiana for the end head of a motor. Figure 2 shows the die along with the part cast in it.

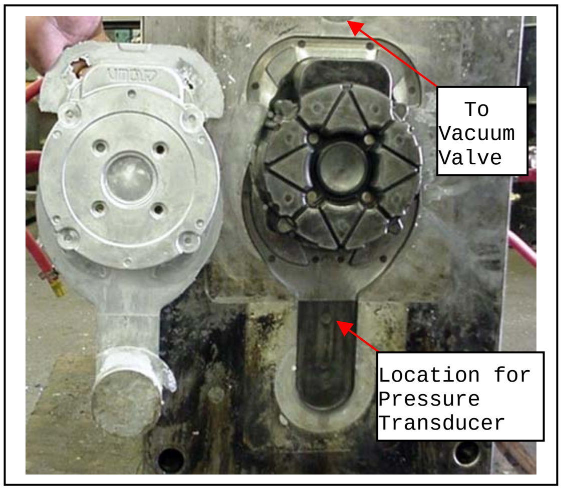


Figure 2: The cast part (end head of motor) and the die.

The tooling included 26 ejector pins and a vacuum valve. The ejector pins forms a slip fit with the die resulting in a 0.0005-0.001 inch maximum clearance. Figure 2 shows the location of the vacuum valve has been shown in Figure 2. The part was expected to vent through the vacuum valve, the ejector pins and the parting line.

The part was run without melt for various configurations. These included the following: all open, vacuum closed, parting line closed, ejector and parting line closed, and all closed. The pressure transducer was used to measure the pressure as a function of time in the runner. The tests were done with a clean die. Silicon rubber was used to seal off the ejector pins. It was found that the parting line sealed quite well by itself and hence silicon rubber was not used for it.

Figure 3 shows the pressure inside the cavity from the various dry runs.

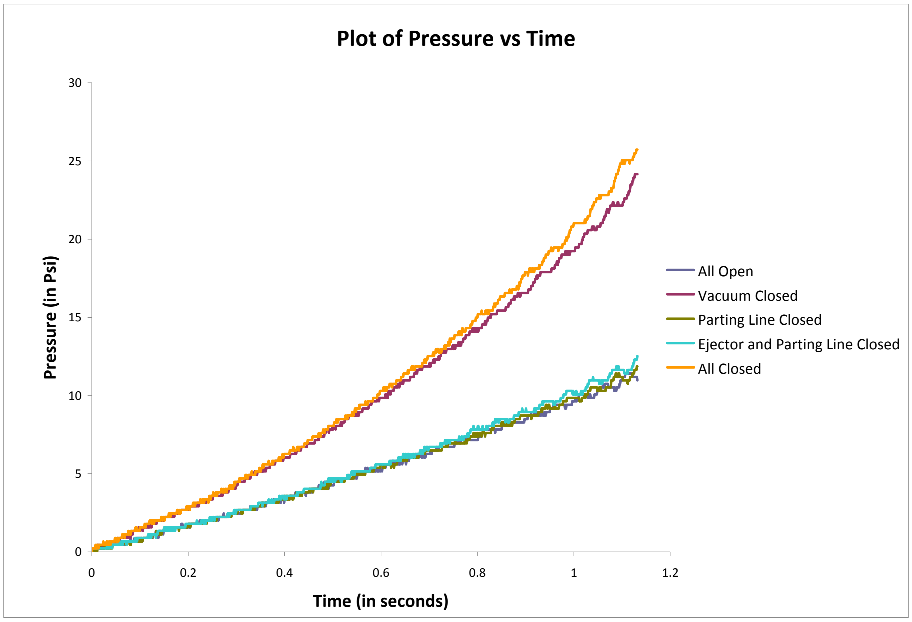


Figure 3: Experimental results of pressure (in Psi) plotted against time (in sec) for the dry runs.

The curves in Fig. 3 show the pressure inside the cavity relative to the atmospheric pressure outside. It is clear that the vacuum valve was the primary source of venting. This can be inferred by the difference between the light blue "Ejector and Parting Line Closed" and violet "All Open" curves. Ejector pins that were not sealed caused a pressure drop in the cavity of less than 2 Psi. This can be seen by the difference between the red "Vacuum Closed" and orange "All Closed" curves. The "All Open" and the "Parting Line Closed" curves were almost identical, indicating that the loss at the parting lines was insignificant.

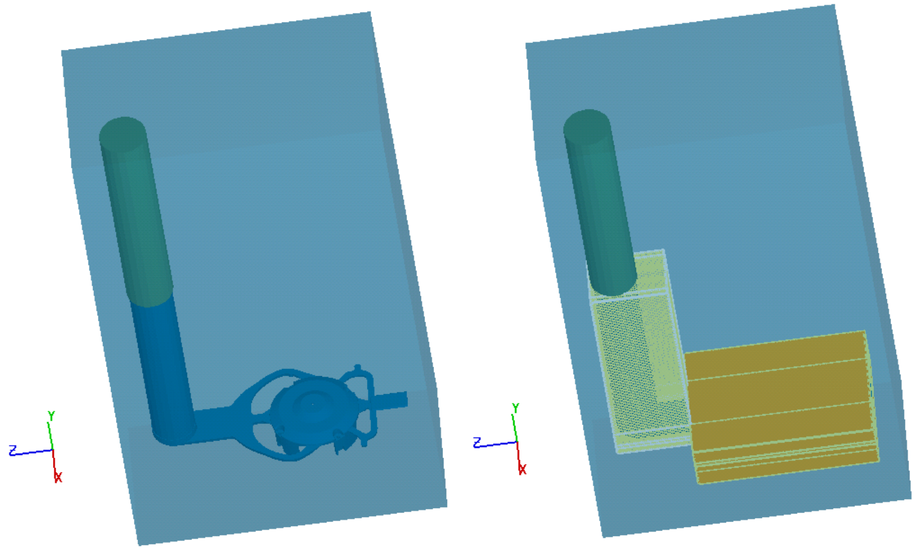
These experimental results were used to calibrate the simulations done in ***FLOW-3D®***. In the next section we will discuss the problem setup and simulation results.

COMPUTATIONAL SETUP

A preliminary model was setup in ***FLOW-3D®*** to calibrate the residual losses or leakages occurring in the cavity. Two simulations of the "All Closed" injection experiment were done. In one case, the air inside the cavity was modeled as a compressible gas and in the other case as an adiabatic bubble. The results from these two simulations were compared to validate the adiabatic bubble model and to determine any residual leakages occurring in the system.

The volume of the piston was calculated with the diameter of the biscuit of 3.25 inches and the stroke length after the pour hole of 16 inches. The initial volume of the part including the runner system plus the piston volume was 160.95 cubic inches. The initial pressure was set to atmospheric pressure. In the final position of the piston the final volume in the cavity was 28.23 cubic inches. This gives a final pressure of 169 psi using the adiabatic equation of state.

Figure 4 shows a snapshot from the simulation setup. This shows the computational mesh used in the problem. Approximately 1 million cells were used in the mesh in order to capture the finer details in the geometry.



(a) **(b)**

Figure 4: A snapshot of the geometry (a) without mesh and (b) with computational mesh.

Figure 5 shows the comparison between the results of the two simulations. Curve 1 shows the pressure when the gas is modeled as a compressible gas. Curve 2 shows the pressure when the gas is modeled as an adiabatic bubble. The results show an excellent agreement between the two approaches for the "All Closed" case. Therefore the adiabatic bubble model was used in the remaining simulations. It is also notable that the peak pressures reached in these simulations are much higher than the peak pressures seen in the all closed curves from the experiments. It was assumed that this is due to presence of residual leakages like those through the shot sleeve or the parting plane**.**

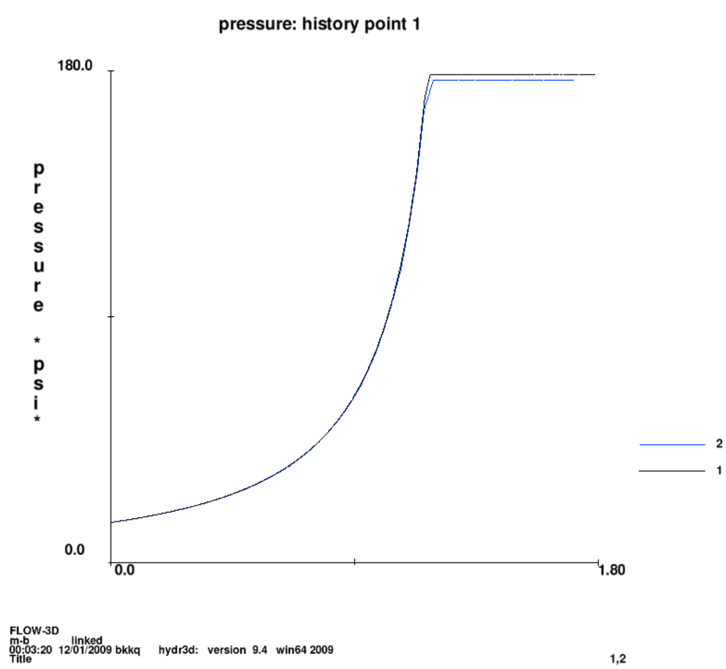


Figure 5: Pressure curves from the "All Closed" for 1-compressible and 2-adiabatic simulations.

RESULTS AND DISCUSSION

In order to quantify the losses due to the residual leak, the ejector pins and the vacuum valve, the following approach was used. Valve 1 was used to represent the combined losses due to the residual leak and the ejector pins. This cumulative loss was expected to come into play when the vacuum valve was closed. A simulation was run in ***FLOW-3D®*** with Valve 1 and the results were compared with the "Vacuum Closed" curve from the experiments. The cumulative loss coefficient was varied for Valve 1 in order to match the experimental data. Each simulation ran in less than two minutes. Pressure plots for both computational and experimental "Vacuum Closed" are shown in Figure 6. The loss coefficient used for the "Vacuum Closed" simulation was 3.73e-6 $m^2/\sqrt{(kg/m^3)}$.

In the second series of simulations all the losses were combined, the residual leak, the loss at the ejector pins, and the loss at the vacuum valve. This case (Valve 2) was expected to correspond to the "All Open" case from the experiments. The valve was calibrated by altering the cumulative loss coefficient until there was a good agreement with the experimental data. The pressure plots for computational and experimental "All Open" curve are shown in Figure 6. The maximum error in this case was close to 1 Psi. The loss coefficient used for the "All Open" simulation was 6.4e-6 $m^2/\sqrt{(kg/m^3)}$.

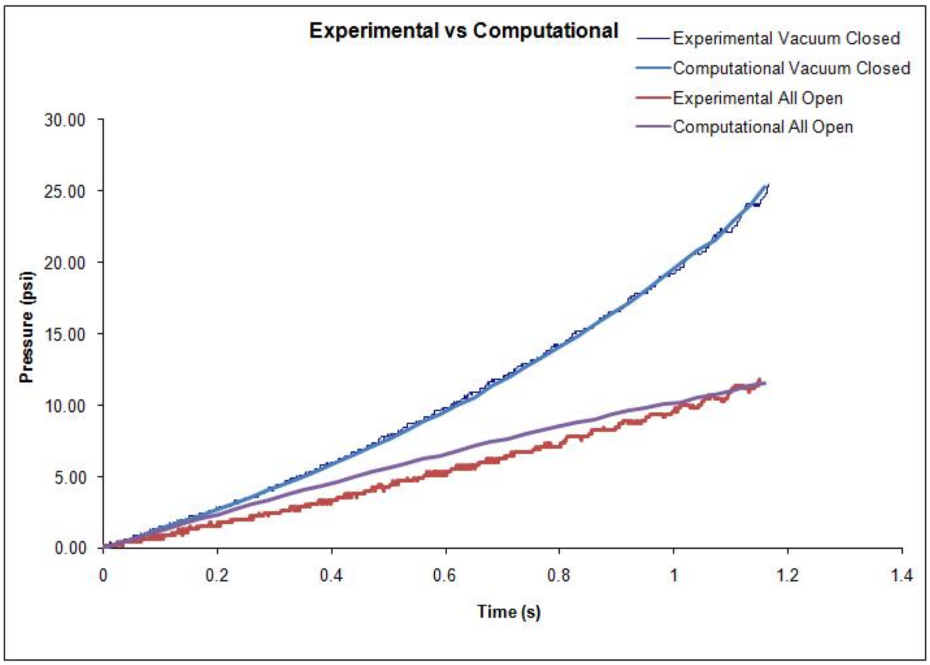


Figure 6: Comparison of experimental and computational results.

The results for this die show that a vacuum valve would not have been necessary for this particular part. This could be partly due to the extended runner system for the valve which acts as a huge overflow. The residual loss through the shot sleeve, ejectors, parting line, and any other region which may act a vent is significant. This can be seen by the difference in pressures (176 psi) between the computational all closed and the experimental all closed cases. As the part is run these results might change due to flash at the parting line creating a larger vent or flash closing the ejector pins leading to lower venting. The amount of venting of course would be different for different types of cast parts. The use of the adiabatic bubble and valve models in ***FLOW-3D®*** allows the user to design and simulate venting in their parts.

CONCLUSION

Many authors have tried to model the flow losses at vents using the Darcy-friction factor and Moody's diagram[5] and Fanno flows where compressibility effects are taken into account[6]. We have shown that these losses can be modeled through the use of simple adiabatic bubble and valve models in ***FLOW-3D®.***

In future this model needs to be used in conjunction with an actual metal fill in order to study the porosity in the part due to improper venting. The valve model also needs to be used in a broader framework which looks at compressible flow losses occurring at vents under certain conditions as well as the effect of different geometries, and gas densities on the cumulative loss coefficient.

ACKNOWLEDGMENTS

We are grateful to Littler DieCast in Albany, Indiana for allowing us to use their facilities for the Injection Experiments.

REFERENCES

1. White, F.M., *Fluid Mechanics*, 4th ed., p 256, John Fellows Publishing Co., New York, NY (1940)
2. *Flow of Fluids Through Valves, Fittings, and Pipe,* Crane Technical Paper No. 410, Joliet, IL: Crane Co., 1988.
3. C.W. Hirt and B.D. Nichols, "Volume-of-Fluid (VOF) Method for the Dynamics of. Free Boundaries," J. Comp. Phys., 39, 1981, pp. 201-225.
4. ***FLOW-3D®*** v 9.4 Manual
5. *Mold Filling Simulation of High Pressure Die Casting for Predicting Gas Porosity,* Modeling of Casting, Welding, and Advanced Solidification Processes X, TMS (The Mineral, Metals, & Materials Society), 2003, pp. 335
6. *Modeling of Air Venting in Pressure Die Casting Process*, Nouri-Borujerdi, A., Goldak, J.A., AD, Journal of Manufacturing and Science and Engineering, ASME, 2004