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*Research Note*

# Analysis of Vacuum Venting in Die Casting

**A. Nouri-Borujerdi**[1]

The present study is undertaken to calculate the rate of change of pressure and residual air mass in die casting for vacuum venting under choked flow conditions. In these calculations, the influence of friction factor, due to roughness and vent air velocity change through the Mach number, has been taken into account. The results show that there is a critical area ratio below which the pressure and vent inlet Mach number increase with time and above which decrease with time. In addition, for an area ratio less than the critical area, the rate of change of residual air mass seems to be more changed at the late stages than at the early stages of the filling time. The picture is reversed for a larger area ratio. This critical area ratio depends on vent area, filling time, evacuated volume, the initial pressure and temperature of the air in the die cavity.

## INTRODUCTION

In a high-pressure die casting process there are many effects that cause porosity and poor surface finish in many die-casting products. The presence of high porosity can negatively influence thermal and mechanical properties such as yield strength, ultimate tensile strength, ductility and modulus of elasticity. Effects that influence porosity are air entrapment, shrinkage of molten metal during solidification, insufficient vent area, lubricant evaporation and incorrect placement of the vents [1,2]. A possible solution to reduce or eliminate this porosity is to apply a vacuum and extract gas before it has the opportunity to mix with the liquid metal. Vacuum applications have been employed since the discovery of the die casting process and it was the late 1950's when the first parts where produced on a large scale using vacuum die casting technology [3]. In spite of equipment cost and its maintenance, some benefits of applying the vacuum die casting process are: Improvement of quality and surface finish, extended life of die casting machine, lowering or elimination of flash, less die stress or distortion and more.

Traditionally, the die filling process in pressure die casting is divided into three stages. In the first stage, the plunger advances slowly until the base of the shot sleeve is covered fully with molten metal (Figure 1). In the second stage, the die cavity is filled at a virtually constant pressure and air is expelled through a vent to a vacuum tank. The last stage is typified by a high rise in packing pressure when the die cavity is fully filled.

Wolodkowicz [3] described that the main causes of poor surface finish are turbulent metal filling the die cavity and gas from rapidly decomposing lubricants with water, which carried the lubricants during die spraying trapped in the die cavity. Metal entering the cavity during the fast shot is split by rapidly expanding gasses into several streams which, later, are fused back together showing characteristic cold flow marks and blisters. Wolodkowicz concluded that by eliminating most of the gasses from the cavity with vacuum valve, the flow pattern was laminar, resulting in a uniform and blister-free surface on the casting. It should be noted

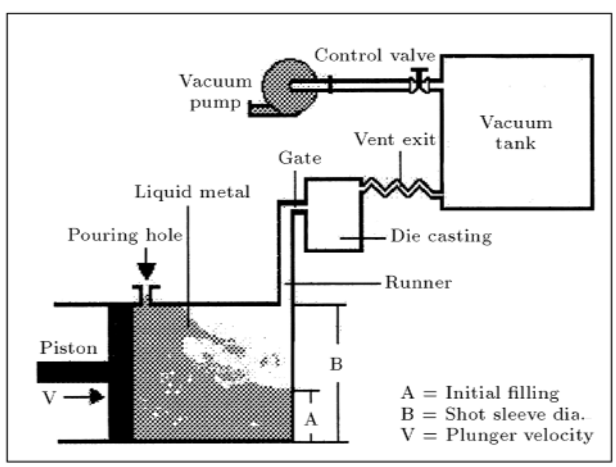


**Figure 1.** Schematic of air venting to a vacuum tank in the casting.

1. *Department of Mechanical Engineering, Sharif University of Technology, P.O. Box 11365-9567, Tehran, I.R. Iran.*

that this assertion is, at best, highly controversial and needs more study and experimental work.

Draper [4] reported that the porosity level of casting in a choked flow decreases with an increase of vent area for atmospheric venting. Moreover, it was found that porosity decreases with increasing the vent area or filling time until the vent area or filling time reaches or exceeds a critical value, after which the porosity remains constant. Lindsey and Wallace [5], who neglected friction in the venting system, have shown that in a choked flow, the porosity decreases with a decrease of evacuated volume. These important findings demonstrate that the critical vent area is crucial to the reduction of porosity. The critical vent area is a value under which the air volume flow rate at the vent is equal to the liquid metal flow rate at the gate. In other words, the rate of change of air pressure and residual air mass in the cavity are constant.

Bennett [6] developed a model to calculate the vent area for a cavity evacuated to atmosphere under constant pressure in the cavity and unchoked flow condition during filling time. He calculated the vent area and pressure from the flow through an orifice by assuming air volume flow rate at the vent to be equal to liquid metal flow rate at the gate.

Bar-Meir [7] indicated that in atmospheric venting there is a critical vent area below which ventilation is poor and above which resistance to air flow is minimal. This critical area depends on geometry and filling time.

Lee and Lu [8] proposed a new mathematical model for calculation of the induced cavity air pressure. In this model, air discharge through rectangular vents is modeled by the Poiseuille flow. Venting capability is directly proportional to the width and inversely proportional to the length of the vent. Vent height exerts the greatest influence on the venting capability. They concluded that there was a considerable difference between their model and the traditional model in calculation of the cavity pressure. In order to have an optimum venting condition, vent height should be close to the possible maximum in the vent design of die casting dies.

Karni [9] performed a quasi steady state analysis to describe pressure variations in the cavity for atmospheric venting, taking into account a constant flow resistance in the venting system. The air temperature in the cavity and the air flow in the vent are assumed to be constant and adiabatic, respectively. In these calculations, conditions in the cavity are determined from conditions at the exit for unchoked, as well for choked flow.

Sachs [10] developed a quasi steady model for the maximum mass flow rate from a die cavity, based on an isentropic process in the die cavity. The only resistance to the gas flow was assumed to occur at the entrance of the vent. Sachs indicated that for a choked flow, the pressure ratio was about two between the cavity and the vent exit.

Veinik [11] developed a similar model for an instantaneously choked flow. He assumed that the lowest pressure in the cavity was equal to about two atmospheres and, then, presented the calculation of the vent area as a ratio of air volume to air velocity and filling time. Veinik [12] also introduced friction in the venting system with the lowest pressure of two atmospheres in the die cavity.

In this study, it is desirable to develop a transient model to determine the variation of air pressure and residual air mass in the cavity, under a choked flow condition, due to the friction factor change. In this transient model, air discharges to a vacuum tank through a vent under variable flow resistance. Understanding the relationship between process variables and the vent critical area is another objective of this work. It should be noted that these effects have not been reported before in the literature.

## GOVERNING EQUATIONS

A commercial die casting system with a vacuum tank is depicted in Figure 1. Because of the relatively small resistance to air flow in the unfilled shot sleeve, runner and cavity, compared with the resistance to flow in the venting system, the following model is proposed to simplify the process. The unfilled shot sleeve, runner and die cavity are combined and called the cylinder cavity and, as such, the pressure in the cylinder is assumed to be uniform.

Consider now a one-dimensional flow with friction through a rectangular vent (or duct) with a constant area connected to a cylinder cavity and, also, to a vacuum tank from two ends. The flow would be choked when the pressure ratio between the vent exit and the cylinder cavity is less than the critical value, depending on the pressure drop in the vent. Under this condition, the exit Mach number is one from the start of the filling process as long as the pressure ratio exceeds a critical value. For the case of adiabatic flow with no external work, termed Fanno line flow, the Mach number, as a function of the vent length, can be written as [13]:

$$\frac{4fL}{D_H} = \frac{1}{K}\left[\frac{1}{M_i^2} - 1\right] + \frac{K+1}{2K}\ln\left[\frac{\frac{K+1}{2}M_i^2}{1+\frac{K-1}{2}M_i^2}\right], \quad (1)$$

where subscript $i$ indicates conditions at the inlet plane of the vent and $f$ and $D_H$ are the mean fanning friction factor and hydraulic diameter of the vent, respectively. This equation implies that the entrance Mach number is independent of the pressure and temperature of the vent exit and depends only on the dimensions and resistance of the vent.

Similarly to Equation 1, a relationship is obtained among the inlet Mach number, pressure in the cavity and vent exit by the following equation:

$$\frac{P_c(t)}{P_e} = \left[\frac{K+1}{2}\right]^{0.5} \times \frac{\left[1+\frac{K-1}{2}M_i^2\right]^{\frac{K+1}{2(K-1)}}}{M_i}, \tag{2}$$

where $P_e$ is the air pressure at the vent exit plane.

The mean fanning friction factor depends on the mean Reynolds number and the vent roughness as [13]:

$$f = \frac{16}{\mathrm{Re}} \quad \text{if} \quad \mathrm{Re} < 2300, \tag{3}$$

$$f = \frac{0.0625}{\left[\log\left(\frac{\varepsilon}{3.7D_H} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2} \quad \text{if} \quad \mathrm{Re} \geq 2300, \tag{4}$$

$$\mathrm{Re} = \frac{\rho V D_H}{\overline{\mu}} = \frac{\dot{m}_{\text{out}} D_H}{2A}\left(\frac{1}{\mu_i} + \frac{1}{\mu_e}\right), \tag{5}$$

where $V$ and $\overline{\mu}$ are the average velocity and viscosity of air, respectively and subscripts $i$ and $e$ indicate conditions at the inlet and exit planes of the vent.

A curve fit for the air viscosity, based on the experimental data [14] results in the following equation with a root mean square error of 0.061%:

$$\mu = 1.4805 \times 10^{-14}T^3 - 4.2616 \times 10^{-11}T^2 + 6.85 \times 10^{-8}T + 1.36055 \times 10^{-6}, \tag{6}$$

where $\mu$ is in terms of kg/m.s and $T$, the absolute static temperature, is in Kelvin at a particular point in the vent.

During the filling process, the outgoing air mass from the cavity is:

$$\dot{m}_{\text{out}} = \rho_i A_i V_i = \frac{P_i}{RT_i} A_i M_i \sqrt{KRT_i}, \tag{7}$$

where $\rho, A$ and $V$ are density, vent area and velocity of air. $K$ and $R$ are the specific heat ratio and air constant, respectively.

Considering an isentropic process for air flow between the cavity as a stagnation state and the vent inlet as a nozzle, one has:

$$\frac{T_i(t)}{T_c(t)} = \left[\frac{P_i(t)}{P_c(t)}\right]^{\frac{K-1}{K}} = \frac{1}{1+\frac{K-1}{2}M_i^2}. \tag{8}$$

Introducing $T_i$ and $P_i$ from Equation 8 and, then, substituting the results into Equation 7, it is obtained that:

$$\dot{m}_{\text{out}} = \frac{M_i A_i P_c(0)\sqrt{\frac{K}{RT_c(0)}}}{\left[1+\frac{K-1}{2}M_i^2\right]^{\frac{K+1}{2(K-1)}}} \times \left[\frac{P_c(t)}{P_c(0)}\right]^{\frac{K+1}{2K}}. \tag{9}$$

Applying mass balance for the air in the cavity, the rate of change of the air mass in the cavity is:

$$\frac{dm_c}{dt} + \dot{m}_{\text{out}} = 0. \tag{10}$$

Assuming an isentropic process during the expansion or compression process of the air in the cavity, one has:

$$\frac{T_c(t)}{T_c(0)} = \left[\frac{P_c(t)}{P_c(0)}\right]^{\frac{K-1}{K}}. \tag{11}$$

Applying the ideal gas equation and introducing Equation 11, the air mass in the cavity, at any particular time in terms of its initial mass, is:

$$m_c(t) = m_c(0)\frac{\forall_c(t)}{\forall_c(0)} \times \left[\frac{P_c(t)}{P_c(0)}\right]^{\frac{1}{K}}. \tag{12}$$

Kaye [15] stated that for more than 95% of the plunger stroke, the speed is almost constant and the air volume in the cylinder cavity, as a function of time, is given as:

$$\frac{\forall_c(t)}{\forall_c(0)} = 1 - \frac{t}{t_{\max}}, \tag{13}$$

where $\forall_c(0)$ is the initial volume of the air in the cavity and $t_{\max}$ is the filling time for liquid metal to reach the vent. Allsop [16] recommended $t_{\max}[ms] = 40\times$ average thickness [mm] for the aluminum solidification process.

Exerting Equation 13 into Equation 12 and, then, substituting the result into Equation 10, the final results are as follows:

$$\frac{m_c(t)}{m_c(0)} = (1-t^*)P_c^{*\frac{1}{K}}, \tag{14}$$

$$\frac{dP_c^*}{dt^*} = \frac{KP_c^*}{1-t^*} \times \left[1 - \frac{M_I A^*}{\left[1+\frac{K-1}{2}M_I^2\right]^{\frac{K+1}{2(K-1)}}} P_C^{*\frac{K-1}{2K}}\right], \tag{15}$$

$$t^* = \frac{t}{t_{\max}},$$

$$P_c^* = \frac{P_c(t)}{P_c(0)},$$

$$A^* = \frac{A t_{\max}\sqrt{KRT_c(0)}}{\forall_c(0)}, \tag{16}$$

under the following initial condition:

$$P_c^*(0) = 1. \tag{17}$$

## SOLUTION TECHNIQUE

To determine the residual air mass and pressure in the cylinder cavity during the filling time, numerical integration of Equation 15 is required. If the filling process is supposed to be completed in a number of very small time intervals, the inlet Mach number can nearly be assumed to be invariant. In this case, first a mean value for $M_i$ is guessed at each time step, $\Delta t^*(= 0.0005)$ and, then, the ordinary differential Equation 15 is integrated numerically by the fourth-order Runge-Kutta method. Applying the value of $P_c^*$ into Equation 9 and, then, introducing $\dot{m}_{\text{out}}$ into Equation 5 yields the mean Reynolds number. Using the value of the Reynolds number and invoking Equation 3 or 4, the mean friction factor is calculated. Then, $M_i$ and $P_e$ are determined from the simultaneous solution of Equations 1 and 2. If the difference between the calculated value and the initial guess for $M_i$ is not sufficiently small, the initial guess for $M_i$ is updated and the above calculation will be repeated until a specified convergence tolerance $(< 10^{-6})$ is established. In the next time step, again, a new mean value for $M_i$ is guessed and the above procedure is repeated until $t^* = 1$ is reached.

## RESULTS AND DISCUSSION

The following results have been obtained for vacuum venting through a rectangular vent under choked conditions. The input parameters required for calculation of data are: Initial temperature and pressure of the air in the cylinder cavity, 300 K° and 1 atm, respectively, vent length, 0.2 m, vent roughness, $\varepsilon = 2 \times 10^{-6}$ m and hydraulic diameter, $D_H = 2$ mm, for six values of area ratio, $A^*(0, 1, 2.7, 5, 15, 25$, respectively). The area ratio is defined as a ratio of the vent area times the length traveled by a piston with sonic velocity during the filling time to the initial volume of the cavity.

Figure 2 shows an interesting pattern of pressure variation in the cylinder cavity as a function of time, all for a hydraulic diameter of 2 mm. The abscissa axis is normalized by the filling time for liquid metal to reach the vent. The maximum final pressure occurs for a line of $A^* = 0$. In this case, no air can escape through the vent (or duct) as the air inside the cylinder is adiabatically compressed. On the contrary, the maximum rate of change of pressure occurs for line $A^* = 25$. When the area ratio is equal to the critical value ($A^* = 2.7$), the cylinder cavity pressure reaches ambient pressure and remains constant. In this case, the air volume flow rate at the vent exit is equal to the liquid metal flow rate at the gate. When an area ratio is less than the critical value, the pressure increases, in spite of the fact that vacuum is applied. For a larger area ratio, the pressure falls rapidly below the ambient.

Figure 3 compares the present model results with Bar-Meir's [2] model results, designated by the markers for air pressure in the cavity for two different values of area ratio. There is a considerable difference between the two models results, especially at the late stages. This difference can be attributed to the dependency of the friction factor on the vent inlet Mach number and roughness, taken to be constant in the Bar-Meir model.

Figure 4 illustrates the variations of the inlet Mach number as a function of time for various values of area ratio. When $A^* > 2.7$, the inlet Mach number decreases gradually from an initial value of 0.37 to the final value of about 0.1. In the case of $A^* < 2.7$, the Mach lines are almost straight. It should be noted that for $M_i = 0.37$, the cavity pressure is equal to the ambient pressure and remains constant during the air venting process.

Figure 5 describes the residual air mass in the cylinder cavity versus normalized time for various area ratios. It is observed that, at any particular time, the residual air mass decreases as the area ratio increases. In addition, when the area ratio is larger than the critical limit ($A^* > 2.7$), more air leaves the cylinder cavity at the early stages of the filling time, compared

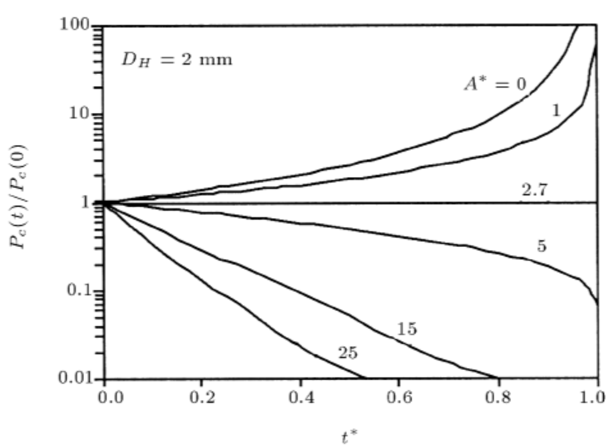


**Figure 2.** Air pressure in the cavity vs normalized time.

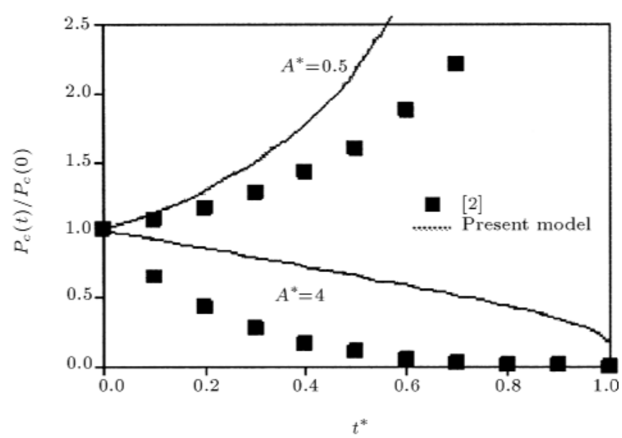


**Figure 3.** Comparison of the air pressure in the cavity for the present model and [2].

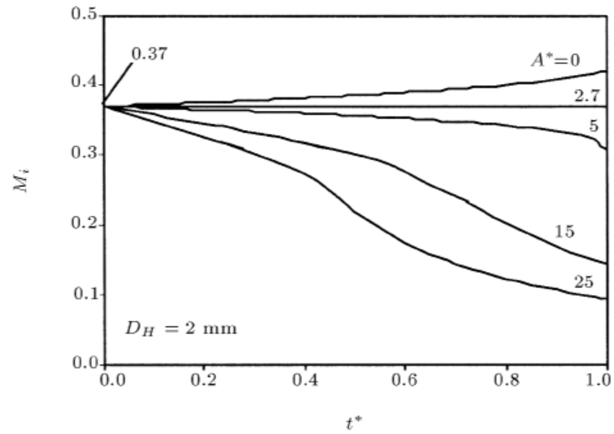


**Figure 4.** Vent inlet Mach number vs normalized time.

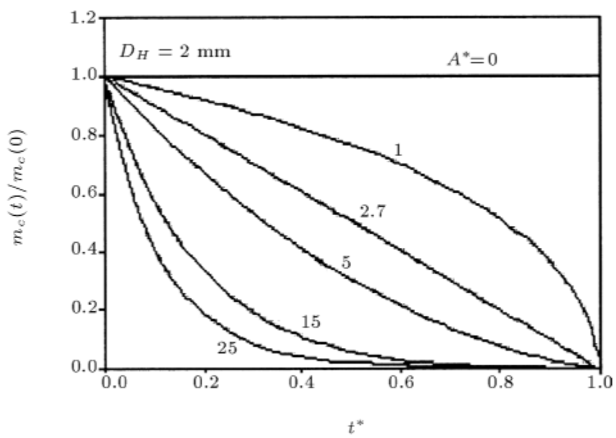


**Figure 5.** Residual air mass in cavity vs normalized time.

with a smaller area ratio ($A^* < 2.7$) under which less air is expelled. This implies that there is a limit to the area ratio under which the residual air mass is a linear function of time.

A comparison of the residual air mass between the results of the Bar-Meir et al. [2] model and that of the present model, is shown in Figure 6. The results show that the air mass in the cavity is one or zero using two models when normalized time approaches zero or one, respectively. There is a considerable difference between the results of the two models when the time approaches the middle of the filling time, because the residual air mass approaches one or zero, according to Equation 14, at the beginning or at the end of the process, regardless of the values of the Mach number and friction factor.

Figure 7 exhibits the variations of $4fL/D_H$ as a function of normalized time, where $f$ is the fanning friction factor and $L$ is the length of the vent. As soon as the air starts to flow in the vent, the value of $4fL/D_H$ reaches 2.93. The vent friction factor is nearly a linear function of time when the area ratio is less than the critical limit ($A^* < 2.7$), while it increases rapidly with time when the area ratio is larger than the critical value ($A^* > 2.7$). These results are in contrast to the results of Bar-Meir [2], Draper [4], Lindsey and Wallace [5], Sachs [10] and Veinik [11] models. The models published by these authors assume that the friction factor remains constant or, at most, can be changed between 3 and 7.

The influence of hydraulic diameter on both friction factor and the limit of the critical area ratio is significant. Comparison between Figures 7 and 8 shows that when the hydraulic diameter changes from 2 mm to 0.2 mm, the limit of the critical area ratio changes from 2.7 to 19.48 and the value of $4fL/D_H$ changes from 2.93 to 265, as soon as the air starts to flow in the vent. It is also observed that the variations of $4fL/D_H$, for area ratios below the critical limit, are more significant for smaller hydraulic diameters. In this case, the friction factor is more nonlinear and less evenly distributed through the time. The minimum points on lines $A^* = 0, 1$ and 5 indicate the transition conditions from a laminar to a turbulent flow in the vent, because the corresponding Reynolds number at these points is about 2300.

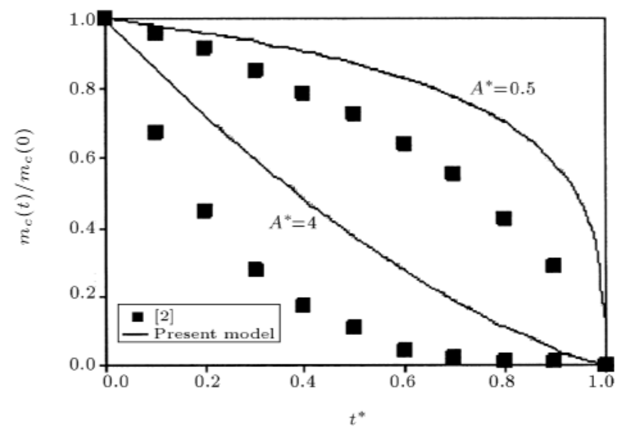


**Figure 6.** Comparison of the residual air mass in the cavity for the present model and [2].

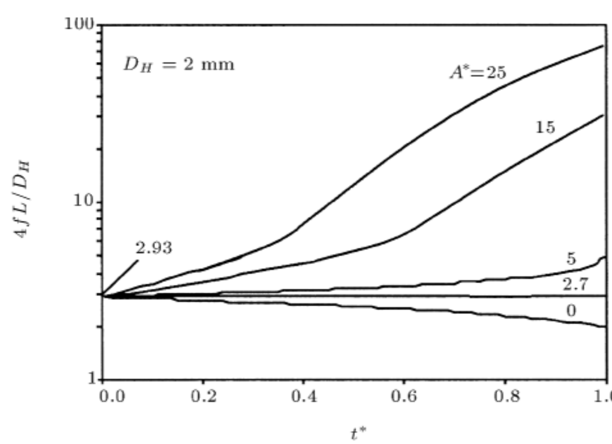


**Figure 7.** Vent friction factor vs normalized time.

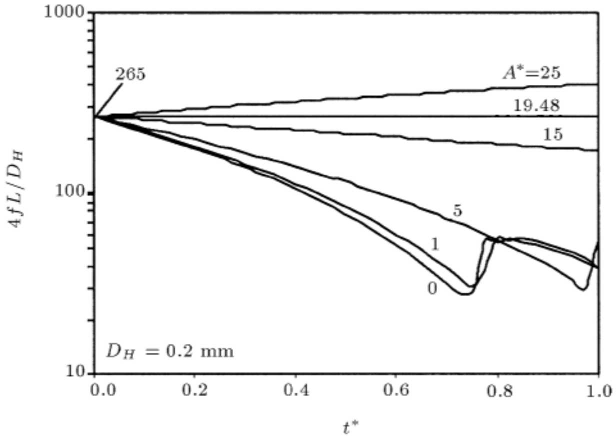


**Figure 8.** Vent friction factor vs normalized time for $D_H = 0.2$ mm.

## CONCLUSION

A mathematical model has been developed to calculate pressure and residual air mass in a cylinder cavity. The model involves the influences of roughness, air velocity and temperature dependent viscosity through the friction factor. Computation is carried out for a rectangular vent with different sizes. The results of the computation were analyzed and some useful findings were obtained.

There is a critical area ratio above which the patterns of pressure, inlet Mach number, residual air mass and friction factor are different from those of the area ratios below the critical limit. In addition, the range of their variations depends on vent area, filling time and initial conditions. Also, the critical limit depends on the hydraulic diameter of the vent.

## NOMENCLATURE

| | |
|---|---|
| $A$ | vent area |
| $D$ | vent diameter |
| $f$ | fanning friction factor |
| $K$ | specific heat ratio |
| $L$ | vent length |
| $m$ | mass |
| $M$ | Mach number |
| $P$ | pressure |
| $P^*$ | $P(t)/P(0)$ |
| $R$ | air constant |
| Re | Reynolds number, $\rho V D_H/\mu$ |
| $t$ | time |
| $t^*$ | $t/t_{\max}$ |
| $T$ | temperature |
| $V$ | velocity |
| $\forall$ | volume of cylinder cavity |

### Greek Symbols

| | |
|---|---|
| $\Delta$ | difference |
| $\varepsilon$ | vent roughness |
| $\mu$ | viscosity |
| $\rho$ | density |

### Subscripts

| | |
|---|---|
| $c$ | cylinder cavity |
| $e$ | exit |
| $H$ | hydraulic |
| $i$ | inlet |
| max | maximum |
| out | outlet |
| ref | reference |
| 0 | initial condition |

### Superscripts

| | |
|---|---|
| | mean |
| $n$ | power |
| $*$ | dimensionless |
| . | rate |

## REFERENCES


1. Brevick, J.R., Duran, M. and Karni, Y. "Experimental determination of slow shot velocity-position profile to minimize air entrapment", *Transactions of 16th International NADCA Congress and Exposition*, Paper No. T91-OC4, Detroit, MI, USA (1991).
2. Bar-Meir, G., Eckert, E.R.G. and Goldstein, R.J. "Pressure die casting: A model of vacuum pumping", *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, **118**, pp 259-265 (1996).
3. Wolodkowicz, A. "Vacuum die casting: Its benefits and guidelines", *Transactions of 16th International NADCA Congress and Exposition*, paper No. T91-071, Detroit, MI, USA (1991).
4. Draper, A.B. "Effect of vent and gate area on the porosity of die casting", *Transactions of American Foundrymen's Society*, **75**, pp 727-734 (1996).
5. Lindsey, D. and Wallace, J.F. "Effect of vent size and design, lubrication practice, metal degassing, die texturing and filling of shot sleeve on die casting soundness", *Transactions 7th SDCE International Die Casting Congress and Exposition*, Chicago, USA, p 10372 (1972).
6. Bennett, C.H. "Venting-the die casting machine becomes an air compressor", *Die Casting Engineering*, pp 22-26 (1990).
7. Bar-Meir, G., Eckert, E.R.G. and Goldstein, R.J. "Air venting in pressure die casting", *Journal of Fluid Engineering, Transactions of the ASME*, **119**, pp 473-476 (1997).

8. Lee, W.B. and Lu, H.Y. "Modeling of air back pressure in die casting dies", *Journal of Materials Processing Technology*, **91**, pp 264-269 (1999).

9. Karni, Y. "Venting design in die casting: An analytical approach", *International NADCA Congress and Exposition*, Paper No. G-T91-OC2, Detroit, MI, USA (1991).

10. Sachs, B. "An analytical steady of the die casting process", Ph.D. Thesis, Columbia University, USA, (1952).

11. Veinik, A.I. "Theory of special casting method", *ASME*, New York, USA (1962).

12. Veinik, A.I. "Thermodynamic factor in metal injection: Effect of friction on gas content and quality", *Transactions of the 4th SDCE International Die Casting, Exposition and Congress*, Cleveland, Ohio, paper 103, USA (1996).

13. Oosthuizen, P.H. and Carscallen, W.E. "Compressible fluid flow", *The McGraw-Hill Companies, Inc.*, New York, USA (1997).

14. Chapman, A.J. "Fundamental of heat transfer", MacMillan, New York, USA (1987).

15. Kaye, A. and Street, A. "Die casting metallurgy", *Butterworth Scientific*, London, UK, p 213 (1982).

16. Allsop, D.F. "Pressure die casting Part 2: The technology of the casting and the die", Pergamon Press, Oxford, UK (1983).