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# Fluid Flow in Tapered Tangential Runners Feeding Thin Gates in Metal Diecasting Dies

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SUMMARY A mathematical model has been developed for the calculation of the flow of fluid through tapered tangential flow channels ("runners") which are designed to feed long thin gates in diecasting dies. Some results are given. The conclusions have been confirmed experimentally.

## 1 INTRODUCTION

Traditionally, metals were cast into sand moulds. Metal moulds were developed, but were still poured in the traditional way, the process being referred to as gravity diecasting. By injecting metal into the dies under pressure ("pressure die casting"), the speed, controllability and versatility of casting production were improved. The mass production of complex, high quality castings in zinc, aluminium and copper alloys became possible.

The economics of the process are very dependent on the design of the metal feed system, which influences the porosity, surface finish, and mechanical properties of castings, and hence the reject rate. Cost savings can be made by reducing the weight of runners and overflows which have to be trimmed off and remelted. If thinner castings can be manufactured, material can be conserved and the weight of the final product reduced.

A feature of recent feed system designs, particularly in dies for producing zinc alloy components, is the use of runners designed to follow the periphery of the casting cavity, continuously reducing in cross sectional area along the direction of flow. Thin gates (0.01 to 1.0 mm thick) are cut along all or part of the length of the runner, depending on the casting geometry. In the diecasting industry these flow channels are referred to as tapered tangential runners. A typical casting (trimmed and as cast) is shown in Figure 1. The tangential runners and gates are designed to minimise the metal flow distance in the die cavity, to obtain correct gate velocity and to obtain a favourable flow pattern from the point of view of air entrapment and the minimising of surface defects. For zinc alloy 3, the design flow velocity in tangential runners is usually in the range 20-40 $m.s^{-1}$, while the gate speed, i.e. the speed at which metal enters the die cavity, is in the range 30-60 $m.s^{-1}$. Cavitation and die erosion problems preclude the use of higher speeds, while low speeds encourage the premature freezing of thin gates.

This paper will describe theoretical and experimental work carried out to study molten metal flow in tapered runners. The work was supported in part by the International Lead & Zinc Research Organization, New York, and the authors wish to acknowledge the assistance of CSIRO colleagues, including Dr. F. de Hoog of CSIRO Division of Mathematical Statistics, Canberra.

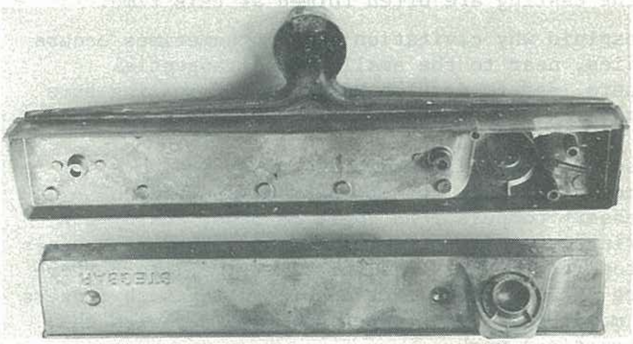

Figure 1. A thin walled zinc diecasting fed from twin tapered tangential runners.

## 2 GENERAL FEATURES OF THE FLOW OF FLUID IN TAPERED TANGENTIAL RUNNERS, AND AIM OF THE WORK

When fluid enters a tapered tangential runner, gated along its entire length, two alternative flow paths are available. The fluid can flow along the runner, in which case it must accelerate, since the cross sectional area is decreasing. Alternatively, some fluid can change direction and flow out of the gate at some angle measured relative to the normal to the gate (Fig. 2). Clearly the flow will be split between the two flow paths, with increased flow through the gate as the fluid front advances along the runner. When the front reaches the end of the runner, one flow path is eliminated and all flow must be through the gate. Hence, there is a sudden change in the velocity distribution in the runner, giving rise to a pressure shock. The excess energy is in fact dissipated as increased gate velocity at the small end of the runner, as shown by water analogue studies (1), and by experience with erosion in dies.

Finally, steady state flow is obtained, though this is modified by increased back pressure as the die cavity is filled.

This relatively complex behaviour can be contrasted with the simple relationship for a straight runner and gate, with minimal change of flow direction and simultaneous operation of the entire gate width. The relative velocity in runner and gate can be readily calculated from the flow continuity equation:-

$$\frac{u_g}{u_{in}} = \frac{A_{in}}{A_g} \qquad (1)$$

where $ug$ = gate velocity normal to gate

$u_{in}$ = velocity in runner

$Ain$ = area of runner cross section

$Ag$ = area of gate

The aims of the research were:-

To calculate the relationship between pressure and flow rate, for any design, for steady flow.

To calculate the velocity and direction of flow from any part of the gate, so that the fill pattern in the cavity could be predicted.

To predict the performance of runners during the transient stage, where the metal front is moving along the runner and flow from the gate has already commenced. This transient phase is an appreciable fraction of the total cavity fill time, which is usually in the range 5-100 milliseconds. It is particularly important to know the gate velocity during the transient phase, since surface defects in the casting are often formed at this time.

To explain why cavitation erosion sometimes occurs in dies, near to the small end of tangential runners, and to develop means of eliminating this problem.

These purposes were achieved by developing a mathematical model of the system, so that the necessary computations could be made, and by conducting water flow experiments on adjustable models of tapered runners. At the same time, the performance of production dies incorporating such runners was monitored. This paper deals mainly with the mathematical work.

## 3 DERIVATION OF THE MATHEMATICAL MODEL

### 3.1 Basic mathematical relationships

An approximate solution was obtained by dividing the runner into a number of elements and considering the flow into and out of each element. The accuracy was dependent on the number of elements chosen. Bernouilli's equation for the energy of a fluid was applied to the flow at each element. The potential energy term was neglected, since it is negligible for the high velocities and small changes in position which occur in diecasting practice. Empirical relationships for the pressure loss due to geometric shape and surface roughness factors were used in the analysis, though there will be errors due to the transient nature of the flow situation. Previous experimental work on pressure losses in the gooseneck and nozzle of hot chamber diecasting machines during the short period of metal injection (2) suggest that the errors are acceptable.

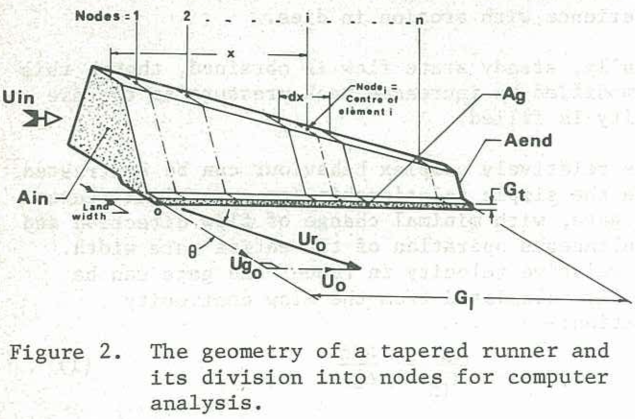


Figure 2. The geometry of a tapered runner and its division into nodes for computer analysis.

It is assumed that the molten metal is a Newtonian fluid, flowing steadily along the runner axis and from the gate. The approximate model divides the runner into a number n of discrete elements, whose centers are called the nodes as shown in Fig. 2. The flow can then be assumed to be filling n separate cavities simultaneously through n separate gates. For example, the metal flow rate at node 2 is equal to the sum of the metal flow rate at node 3 and the metal flow rate through the gate at node 2. This concept is known as the continuity equation which can be expressed as:

$$u_i\ A_i = u_{i+1}\ A_{i+1}\ ug_i\ Ag_i \qquad (2)$$

where $u_i$ and $u_{i+1}$ = metal velocity in the direction along the runner at node i and i+1 respectively.

$ug_i$ = metal velocity in the direction normal to gate element i

$A_i$ and $A_{i+1}$ = cross-sectional area of runner at node i and i+1

$Ag_i$ = gate area at element i

If a particular node i is considered, the velocity of the metal emerging from the gate at node i, is the resultant of velocities $u_i$ and $ug_i$.

Its magnitude $ur_i = \sqrt{ug_i^{\,2} + u_i^{\,2}} \qquad (3)$

and its direction is given as:

$$\theta = \text{artan}\ \frac{u_i}{ug_i} \qquad (4)$$

where

$ur_i$ = the magnitude of the resultant velocity emerging from the gate at angle $\theta_i$ to the normal to the gate.

Now with the above-stated simplifying assumptions, Bernouilli's equation can be applied directly between node i and i+1 which gives:

$$p_i + \frac{\rho}{2}\,u_i^{\,2} = p_{i+1} + \frac{\rho}{2}\,u_{i+1}^2 + \frac{4fdx}{de_{i+1}}\,\frac{\rho}{2}\,u_{i+1}^2 \qquad (5)$$

and between node i, i+1 and the flow out of the gate gives:

$$p_i + \frac{\rho}{2}\,u_i^{\,2} = \frac{1}{C_d{}^2}\,\frac{\rho}{2}\,ur_1{}^2 \qquad (6)$$

$$p_{i+1} + \frac{\rho}{2}\,u^2{}_{i+1} = \frac{1}{C_d{}^2}\,\frac{\rho}{2}\,ur^2{}_{i+1} \qquad (7)$$

Substituting equations (3), (6) and (7) into (5) gives:-

$$\frac{1}{C_d^2}\,(ug_{i+1}^2 - ug_i^2\,) + \frac{1}{C_d{}^2}\,(u_{i+1}^2 - u_i{}^2) + \frac{4fdx}{de_{i+1}}\,u_{i+1}^2 = 0 \qquad (8)$$

where

$de_{i+1}$ = diameter equivalent at node i+1

= 4 x cross sectional area/wetted perimeter f = friction factor derived from Moody's diagram

dx = length of element i

$C_d$ = gate discharge coefficient (to be defined)

3.2 Analysis of the transient phase, during which the runner is being filled. The continuity equation (2) and the flow energy equation (8) derived from Bernouilli's equation can be applied for every node. We assume that at any time during runner fill, there are $n_f$ elements which are full, where $n_f$ is less than or equal to n, the total number of elements. By this means, a set of non-linear simultaneous equations is formulated which can be solved by a standard numerical technique (the Newton-Raphson method). The solution of this set of equations gives the values of the velocity $u_i$, $ug_i$ and $ur_i$. The pressure at every node can be calculated using equations (6) and (7).

3.3 Analysis for Steady Flow.

The analysis of steady flow can be carried out in a manner similar to that for the transient condition. However, this was found to be computationally laborious and expensive, as the Newton-Raphson method requires the solution of a large number of linear equations.

A simpler alternative is to take the limit of equations (2) and (8); that is allowing n to reach infinity. One can thus derive the following equations:

from the continuity equations:

$$\frac{d}{dx}\,(AU) + G_t\,ug = 0 \qquad (9)$$

and from the energy equations:

$$\frac{1}{C_d{}^2}\,\frac{d}{dx}\,(u^2 + ug^2) + \frac{4f}{de}\,u^2 = 0 \qquad (10)$$

for $0 \leq x \leq G_\ell$

To integrate the ordinary differential equations (9) and (10), one can use the Runge-Kutta method, giving the values of u and ug at every integrating point along the length of the runner. The initial conditions to be considered are:

$$\text{at } x = 0 \qquad u\,(0) = uin \qquad (11)$$

$$\text{and at } x = G_\ell \qquad u\,(G_\ell) = 0 \qquad (12)$$

where

$G_t$ = gate thickness

$G_\ell$ = gate length

uin = inlet velocity

## 4 FACTORS AFFECTING THE PERFORMANCE OF RUNNERS

### 4.1 Relative Roughness of the Surfaces.

Smooth surfaces are advantageous and surface finishes of order 0.0005 mm CLA were therefore assumed in preliminary calculations. Surface roughness affects the velocity variation along the gate length, and the flow through the gate during runner fill.

### 4.2 The Geometry of the Gate

The flow efficiency of the system is influenced by the shape of the gate inlet, since the flow is here changed in direction and accelerated to speeds of 30-60 $m.s^{-1}$. Empyrical loss coefficients or K factors range from zero for a radiused inlet, up to 0.5 for a sharp edged inlet. The total gate loss coefficient $K_t$ includes frictional losses in the gate land and can be expressed as a discharge coefficient in Bernouilli's equation, so that

$$C_d = \sqrt{\frac{1}{1+K_t}}$$

In practice gate lands are narrow (< 2 mm) to avoid freezing problems, so that the effect of inlet shape is predominant.

### 4.3 Dimensions and Shape of Runners

Calculations were carried out for a family of runners having a trapezoidal cross section of thickness equal to average width and a side angle of $\tan^{-1}$ 0.1. The dimensions were varied in geometric progression up to 400 mm long and the runner area ratio, i.e. the ratio $\frac{Ain}{Ag}$ was made equal to 1.0, 1.25 and 1.67. This ratio controls the flow angle from the gate.

### 4.4 Properties of the Fluid

For zinc alloy 3 at 400°C, the density is 6.13 x $10^3$ kg $m^{-3}$, and the viscosity is 0.0335 Poise. Reynolds number and therefore the friction factor f are readily obtained.

## 5 SOME CALCULATED RESULTS

Comprehensive results have been published previously (3,4).

### 5.1 Flow Angle and Gate Velocity

The graphs of Fig. 3 apply to steady flow in runner-gates designed for constant flow angle along their length. Clearly the flow continuity equation (1), used to calculate the gate velocity for traditional runner designs, is not directly applicable to tangential runners. By varying the gate thickness and the runner cross section along the runner length the flow angle can be varied, so that the flow stream is convergent or divergent depending on the requirements for filling the die cavity.

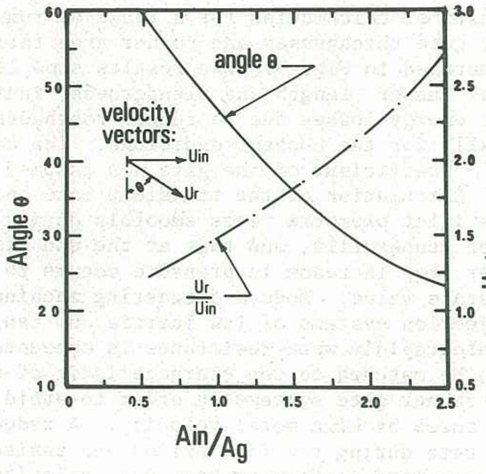


Figure 3. The velocity and direction of flow from a gate on a tapered runner.

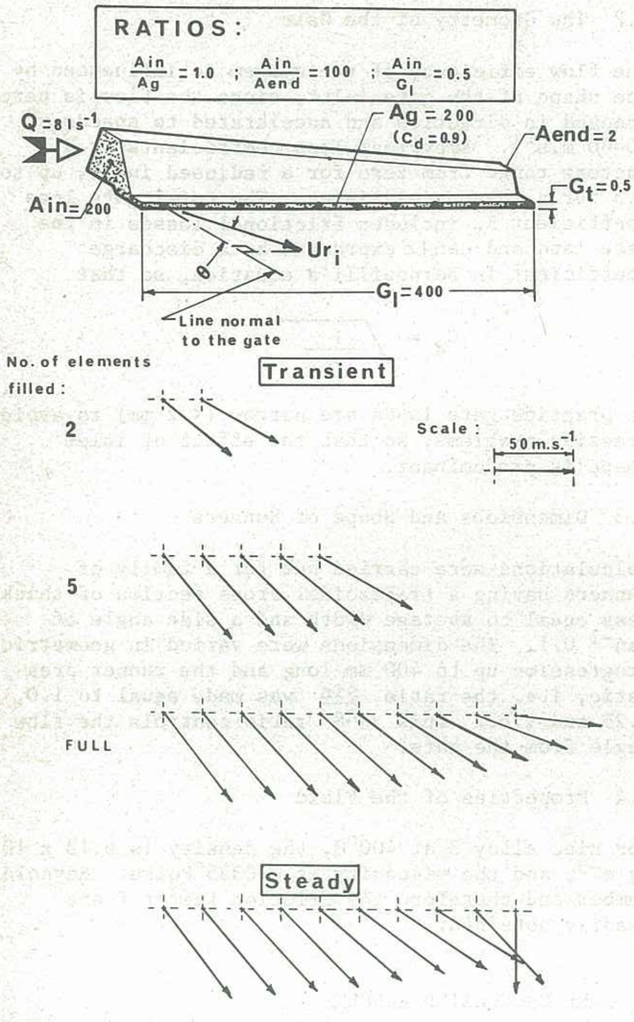


Figure 4. Variations in the direction and velocity of flow from the gate during the period of runner fill.

During the transient phase of runner fill the direction and velocity of flow from the gate vary continuously. In Fig. 4, computer plots of velocity vectors are illustrated at 20%, 50% and 100% runner fill. In this case the runner was divided into 10 nodes. The step change from the 100% fill condition to the steady state condition is clearly illustrated.

### 5.2 The Pressure at Entry to a Tapered Tangential Runner

The results of calculation for a range of runner lengths, gate thicknesses and runner area ratios are summarised in Fig. 5. The results show little effect of runner length and slenderness, indicating that energy losses due to runner roughness were small, for the chosen conditions. The discharge coefficient of the gate was assumed to be 0.9. Calculation of the transient case shows that the inlet pressure rises smoothly during the period of runner fill, and that at the end of fill a further step increase in pressure occurs to the steady state value. Modern diecasting machines have injection systems of low inertia and can decelerate rapidly when resistance is encountered. They can be matched to the characteristic of tangential runner gate systems in order to avoid die damage caused by high metal velocity. A reduction in flow rate during the fill period can assist in obtaining a more uniform average gate velocity overall.

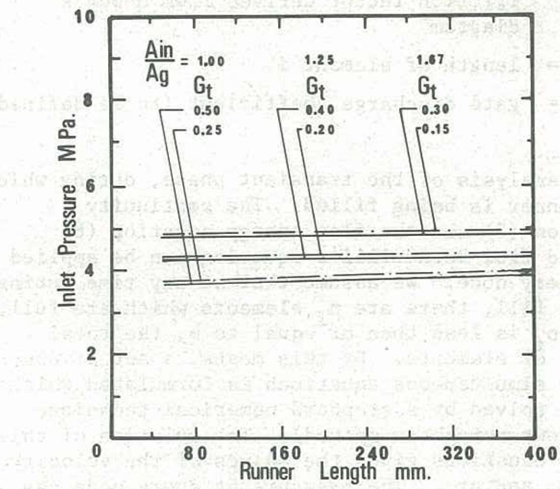


Figure 5. The runner inlet pressure required for flow of molten zinc alloy 3 at a true gate velocity of 40 $m.s^{-1}$.

### 5.3 The Volume of Metal Passing through the Gate During Runner Fill

Calculation showed that for the chosen geometries, a volume flow of 50-70% of the runner volume would be fed through the gate during this period. For certain thin castings, this could represent an appreciable fraction of the casting volume. An important diecasting process parameter is the total time to fill the casting, which has a major effect on quality. This work clearly shows that the fill time must be calculated from the time when metal flowing in a tangential runner reaches the first section of gate. Since the runner takes an appreciable time to fill, higher metal flow rates and larger gates may be needed, when tangential runners are used, relative to traditional runner designs.

## 6 EXPERIMENTAL RESULTS

Experimental work and instrumented production die trials have confirmed the calculated data, which is now being used in die design. Pressures are often increased by the freezing of a thin skin of metal in the gate, this effect being dependent on die and metal temperature. The pressure shock problem has been solved by trapping a pocket of air in a cavity at the small end of the runners. The compression of this air serves to attenuate the shock (Fig. 6).

Figure 6. Tapered runner with shock absorbing overflow.

## REFERENCES


1 DAVIS, A.J., SIAUW, T.H., CUNNINGHAM, A., EICKE, J., BENNETT, W.J.: "Some Experiments on the Performance of Tapered Runners", Transactions S.D.C.E. 1979 ; G-T79-054.

2 SIAUW, T.H. & DAVIS, A.J.: "Theoretical Estimation of the Pressure Required to Inject Molten Metal into Die Cavities", Transactions S.D.C.E. 1977; Paper No. G-T77-072.

3 SIAUW, T.H. & DAVIS, A.J.: "Fluid Flow in Gate and Runner Systems", Progress Report No's 1, 2 and 3. ILZRO Contract No. ZM-254.

4 SIAUW, T.H. & DAVIS, A.J.: "Flow Analysis in Tapered Runners", Transactions S.D.C.E. 1979; Paper No. G-T79-052.