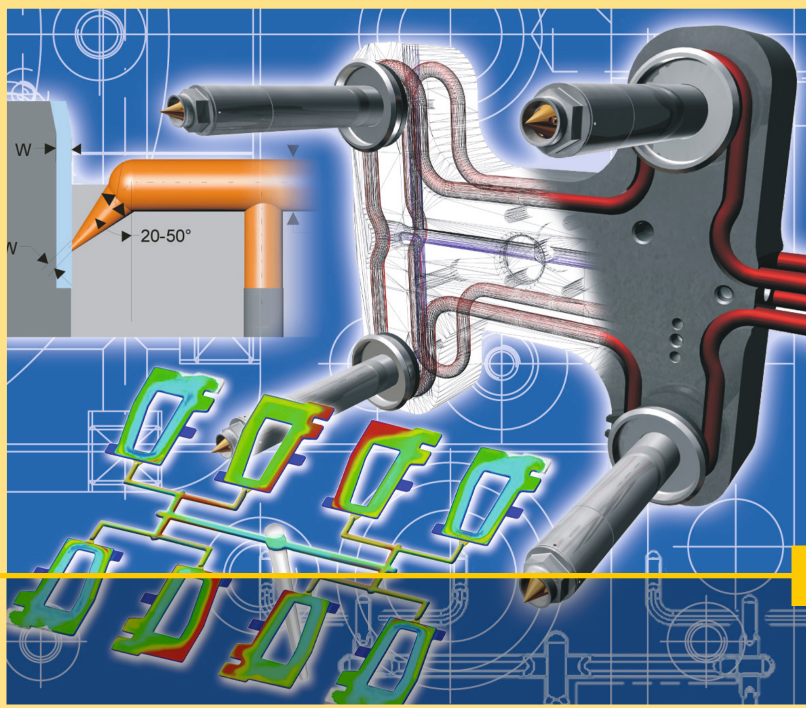
John P. Beaumont

# Runner and Gating Design Handbook

## Tools for Successful Injection Molding




3rd Edition

HANSER

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# Preface

Quality management methods, such as *Design for Six Sigma*, stress the critical review of fundamentals in order to identify and eliminate potential problems before they take their toll on the manufacturing process. In developing a mold design to produce an injection molded plastic part, one of the most fundamental and influential components is its melt delivery system. It also turns out that the melt delivery, or runner, system is probably the most underappreciated and misunderstood component of the injection mold. This makes it a prime candidate for critical review, particularly for the conscientious molder striving to improve his/her bottom line.

The melt delivery system begins with the injection molding machine's nozzle and continues into the mold, progressing through the sprue, runner, and gate. Though the melt may only experience these flow channels for a fraction of a second, their effects are dramatic and result in the most extreme conditions experienced by the plastic melt in any phase of nearly any plastics processing method. Shear rates in gates commonly exceed 100,000 $s^{-1}$ and localized melt temperature in high shear laminates can spike at as much as 200 °C, at rates that can exceed 1000 °C/s. Due to the extremity of these conditions, the actual effect of these conditions on the melt is not well understood. Most material characterization methods do not even come close to measuring melt conditions under these extremes. Viscosity vs. shear rate data are generally developed at a maximum of 10,000 $s^{-1}$, DSC data at less than 32 °C/min, and PVT data at less than 3 °C/min. As a result of the limitations of material characterization methods as well as solution modeling and meshing issues, today's injection molding and fluid flow simulation programs are still struggling to accurately predict the extreme non-homogeneous asymmetric melt conditions developed in a branching runner. The challenge of dealing with these conditions has generally been underestimated.

The influences of these extreme melt conditions developed in the runner are just beginning to be understood. One of the most significant is the realization that the combination of laminar flow and high perimeter shear in a runner results in extreme non-homogenous melt conditions across a runner. Not only can a 200 °C variation in melt temperature exist but, as a result of the non-Newtonian characteristics of the melt, the viscosity may easily vary 100-fold from the zero shear conditions in the center of a flow channel to the extreme shear conditions around the perimeter. This creates significantly asymmetric melt conditions when the melt branches in a runner or part-forming cavity. The conditions developed in the runner continue into the part, corrupting the expected filling pattern and influencing how the part is packed, its mechanical properties, shrinkage, and warpage. These are all factors that are hardly known by most in the molding industry and their dramatic effects are rarely fully appreciated. The influence can be particularly acute in two-stage injection processes such as gas assist, structural foam, MuCell®, and co-injection.

As stated earlier, the melt delivery system consists of the molding machine's nozzle, sprue, runner, and gate. Each of these components, or regions, can have a significant influence on both the process and the molded part. Process effects include the ability to fill and pack the part, the injection fill rate, the clamp tonnage, and the cycle time. Effects on the part include size, weight, mechanical properties, and variations in these characteristics between parts formed in different cavities within a multi-cavity mold.

Despite the significant influence that the melt delivery system has on the molding process, its various components are generally poorly designed relative to the time, effort, and cost put into the other components/regions of a mold and molding machine. This book bridges the critical gap left by other publications dealing with injection molding, which generally touch only briefly on the design of the melt delivery system and its relationship to successful injection molding. In particular, the lack of information on cold runners needed to be addressed. Though a fair amount of published data on hot runners are available, these data are generally heavily influenced by the bias of companies that sell these systems. There are over 50 companies offering hot runner systems and components commercially, while there is no company at all offering cold runner systems. As a result, one can imagine the lackluster image of cold runners, as there is no company commercially promoting them.

Evidence of the lack of understanding of runners includes the fact that the significant effects of shear-induced flow imbalances in runners were not documented, or clearly understood, until 1997 when I published the first journal article on this phenomenon. For the first time, it became obvious that the industry standard "naturally balanced" runners were creating significant imbalances. Melt filling imbalances, developed from shear-induced melt variations, were found to be the norm in most of the industry standard geometrically balanced runner designs being used. This phenomenon was being overlooked by the entire molding industry for both cold and hot runner molds. In addition, the industry's leading state-of-the-art mold-filling simulation programs had been developed without the realization of the shear-induced imbalance. As a result, these programs did not predict the imbalance and left the analyst with a false impression that these runners provided uniform melt, filling, and packing conditions. The problem still exists today and should be considered when using analysis programs.

Of particular interest is the evolution of the runner from a basic necessity required to connect the injection unit and the mold's cavity to its emergence as a significant process tool. Newer melt rotation technologies, such as MeltFlipper® and iMARC™, have introduced the concept of 3D injection molding.

This book takes an independent view of both hot and cold runners, trying not to make a judgment as to which is best for a given application. Rather, it addresses some of the critical design issues unique and common to both. The early chapters lay a foundation for designing runners by establishing an understanding of the rheological characteristics of plastic melt and how the influence of runner design and gating positions can affect the molded part. Chapter 4 provides important strategies for runner designs and gating position, which are critical to the successful molding of a plastic part. Chapter 5 provides an overview of the melt delivery system, followed by Chapter 6 and 7, which teach the development and solutions to shear-inducted imbalances. These three chapters (5, 6, and 7) address issues which are common to both cold and hot runners, blending basic geometrical channel issues with melt rheology.

Chapter 8 focuses on cold runner designs including specific guidelines for runner and a wide variety of gate designs. Chapters 9 through 13 provide a close look at the design of hot runner systems and their unique capabilities and challenges. Chapter 14 provides a summary on the process of designing and selecting a runner system. Finally, the book concludes with an extensive troubleshooting chapter with contributions from John Bozzelli and David Hoffman.

This 3rd edition of Runner and Gating Design Handbook includes numerous updates and new instructional figures that are scattered throughout each of the 15 chapters. Chapters 6 and 7 include additional information and examples to aid in the understanding of critical shear induced melt variations that are developed in the runners of all injection molds. Autodesk Moldflow analyses and related discussions were added to help further understand the complexities of this phenomenon. Chapters 9 through 12 have expanded on all aspects of hot runners, including the design of manifolds, nozzles, gate tip designs, valve gated nozzles, and valve gate actuation. A new Chapter 15.3, "Injection Molding Process Development", written by Dave Hoffman of the American Injection Molding Institute (AIM Institute), was added.

This book is intended to provide the reader with a better understanding of the critical role the runner plays in successful injection molding. It is hoped that this understanding should go a long way toward reducing mold commissioning times, improving product realization, increasing productivity, improving customer satisfaction, and achieving quality goals such as Six Sigma.

# Acknowledgments

First and foremost I would like thank my wife Betty for her infinite patience and support in my pursuit of various professional endeavors during our many years together, including this book.

Further I would like to thank and acknowledge John Bozzelli, Dave Hoffman, and John Kleese who either directly or indirectly contributed toward material contained in this book. First, I would like to thank John Bozzelli (of Injection Molding Solutions) and David Hoffman (from the American Injection Molding Institute) for their significant contributions to Chapter 15, *Troubleshooting*. John Bozzelli's contribution of an extensive troubleshooting guide (Section 15.2 – *"Injection Molding Troubleshooting Guidelines for Scientific Injection Molding"*) contains a wealth of information based on his extensive industry experience. Hoffman's *"Two Stage Molding Set-Up"*, Section 15.3, provides a practical guide to setting up an injection process. Additionally, some of the material contained in the hot runner portion of this book is based on material presented by John Klees, formerly of Klees Enterprise. John's willingness to share this information is deeply appreciated.

I would also like to thank the various former students that assisted with research, editing, and illustration development for this book. In particular, I would like to thank Scott Cleveland, Amanda Neely, Mason Myers, and Kory Slye, as well as my son Alex Beaumont. Further, I would like to thank both INCOE and Husky who provided both technical information and a number of the figures found in the hot runner sections of this book.

# Contents

# 1 Overview of Runners, Gates, and Gate Positioning

In many cases, the mold design dictates the gating position, although ideally, the optimum gate position should be determined based on part requirements and afterwards the mold design selected to provide for the desired gate position. Available gating positions, and gate designs, are significantly influenced by whether the runner travels along the primary parting plane of the mold (the parting plane where the part forming cavity is defined) or whether it *does not* travel along this plane.

This chapter provides only a brief introduction and orientation of basic runner types and their influence on gate design and gating location. More detail on each of these subjects is presented later in the book.

## 1.1 Primary Parting Plane Runners

In the dominant runner type used in the industry the runner and part forming cavities are located along the same primary parting plane. Primary parting planes, often referred to as the parting lines, are where the mold opens and closes to allow ejection of the molded part and/or of the runner. The primary parting plane is the one where the molded part is formed and ejected. The *primary parting plane runner* is used in *two plate cold runner molds*. A cold runner mold is defined as a mold in which the plastic material in the runner is cooled and ejected from the mold during each mold cycle. Molten plastic material is injected through the runner, the gate, and then into the part-forming cavity. This molten plastic is then cooled by the mold, and when sufficiently solidified, the mold opens and the runner, gate, and part are ejected along the same primary parting plane. Figure 1.1 illustrates the position of the runner within the mold and its ejection from the primary parting plane. Notice that the part and runner are formed and ejected along the same parting plane.

After the molded part and runner are ejected, the mold again closes, creating a flow channel (runner path) between the injection molding machine nozzle to the part forming cavity. As the primary parting plane runner is located along the same parting plane as the part forming cavity, gating into the part is limited to its perimeter, or very near its perimeter. Sub gates, such as the tunnel, cashew, and jump gates, allow gating to be positioned within a short distance from the actual perimeter of the part (for gate designs see Section 8.4).

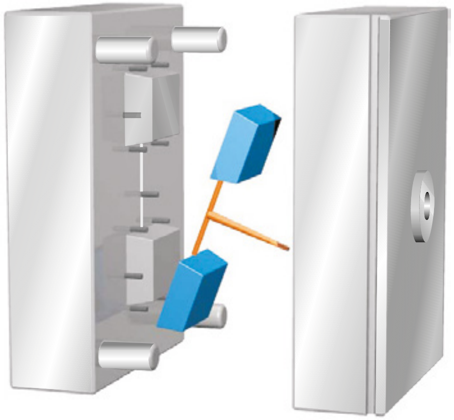

**Figure 1.1** 2-plate mold open and ejecting parts and runner

## 1.2 Sub Runners

A second runner type does not travel along the primary parting plane of the mold. This *sub-runner* generally travels parallel to the primary parting plane, but not along it. The sub-runner can be used in either a cold runner or a hot runner mold.

### 1.2.1 Cold Sub Runners

In a cold runner mold, the sub-runner travels along a second parting plane other than the primary parting plane where the part is formed. The two parting planes are normally parallel to each other and are separated, and partially defined, by at least one mold plate. The sub-runner and part forming cavities are connected by an extension of the sub-runner referred to as a *secondary sprue*. The bridging secondary sprue passes though the at least one separating mold plate and connects to the part-forming cavity through a small gate opening. The secondary sprues are normally parallel to the opening direction of the mold and perpendicular to the sub-runner (see Figure 1.2).

During molding, after the plastic melt in the runner and part forming cavity solidify, the mold will open along the two parting planes. The part is ejected from the opened primary parting plane and the runner (which includes the secondary sprue and gate) is ejected from the opened second parting plane as seen in Figure 1.3.

This type of mold is commonly referred to as a *three-plate cold runner mold*. The terms two-plate and three-plate cold runner molds refer to the minimum number of mold plates required to form and to allow removal of both the part and the solidified runner. With the two-plate cold runner mold, the part and runner are formed and removed between at least a first and second mold plate. With the three-plate cold runner mold, the part is formed and removed between at least a first and second plate and the runner and gate are formed and removed between at least a third plate and often the same second plate used to help form the part.

This type of mold is used when it is desirable to gate the part in a location other than the perimeter. It is commonly used for molding gears where it is desirable to gate in the center hub of the gear.

**Figure 1.2** Cold runner with secondary sprue feeding the part forming cavities in a 3-plate cold runner mold

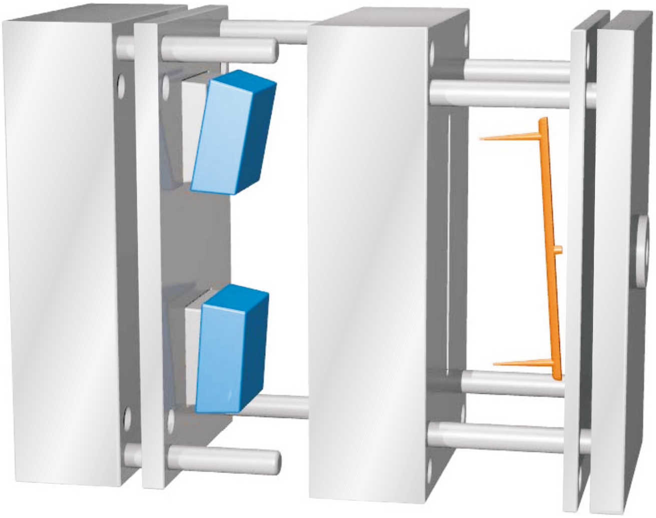

**Figure 1.3** Typical 3 plate cold runner mold open and ejecting parts off the primary parting plane and ejecting the cold runner along the secondary parting plane

### 1.2.2 Hot Sub Runners

A second variation of the sub-runner mold is the *hot runner mold*. This type of runner provides the same gating flexibility as the three-plate cold runner mold. However, unlike a cold runner mold, the melt that travels through the runner remains molten, and is not ejected between molding cycles. The design of hot runner systems is more complex than that of cold runners. Their design and contrast to cold runners are discussed later in Chapter 9.

Two variations of a hot runner are illustrated in Figure 1.4. Here the melt travels in a *hot manifold* along a path, which is normally parallel with the platens of the molding machine. A hot drop, or nozzle, is then used to deliver the melt from the manifold to the part-forming cavity. Special attention is required to isolate the heat from the hot manifold and drop from the part-forming cavity, which requires good cooling. This figure illustrates both a valve gated nozzle (top) and a more conventional open gated nozzle (bottom).

Unlike the cold runner molds, the runner in the hot runner mold remains molten during processing and is not ejected each cycle. Like the three plate cold runner mold, this type of mold provides more gating options than the two-plate cold runner mold.

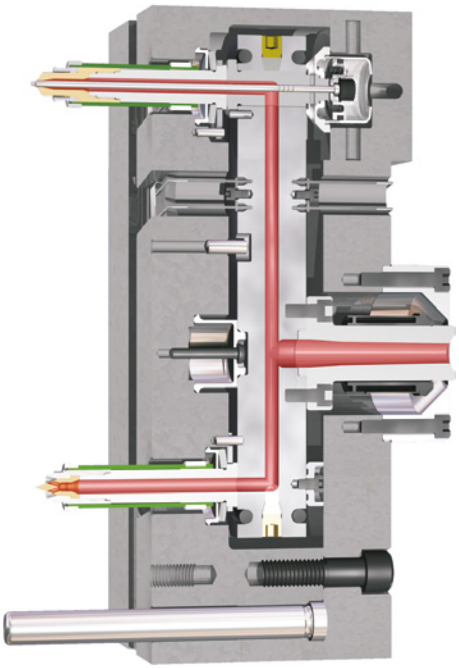

**Figure 1.4** Externally heated hot runner illustrating manifold and drops. The figure illustrates two types of nozzles: the top nozzle is valve gated and the bottom nozzle has a more conventional open gate design (Courtesy: Husky)

## 1.3 Hybrid Sub-Runner and Parting Line Runner

It is common for a mold to contain both a sub runner and a parting plane runner. This is most common when a hot runner is used. Here, the hot runner would deliver the melt to a cold runner, or gate, along the primary parting line. An example is a two-cavity mold, used is to produce the flat donut shaped part shown in Figure 1.5. The hot drop delivers the melt to a cold runner located within the center region of the part. The cold runner then radiates out and gates the part along its inner edge.

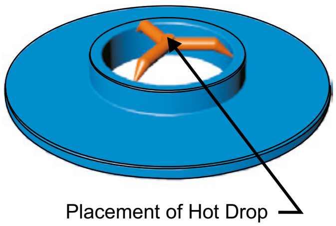


**Figure 1.5** Round part internally gated by a sub-runner which is fed by a hot drop

## 1.4 Gate Designs

Parting line runners are the most restrictive on gating position but provide the greatest flexibility in gating design. The three-plate cold runner mold is limited to restrictive pin point gates, which must allow the gate to be separated, or torn, from the part as the mold opens. Parting line runners can use similar restrictive gates to provide for automatic degating during mold opening, but they are *not required* to use these types of gates. Parting line runners provide for gates to be formed along the parting plane of the mold. This provides significant flexibility in their design to achieve a desired effect. Some of these gates include fan, film, tab, edge, and diaphragm gates. The effects that can be achieved with these gates could include keeping the runner and gate attached to the part to facilitate post-mold handling, using broader gates to limit shear rates and gate region shear stress during mold filling, using broader gates to improve flow patterns across a cavity, and using thicker gates to improve packing.

The hybrid sub-runner and parting plane runner, presented above, increases gating opportunities. An example where this hybrid design might be used is when molding a cylindrical part, where a diaphragm gate is desirable (see Figure 8.31 in Chapter 8). Here, a hot drop feeds directly into a diaphragm gate, which in turn feeds the cavity. The above-mentioned gates, as well as additional gating options, such as valve gates used in hot runners and gates providing automatic degating in cold runners, will be presented in Chapters 8 and 11.

Though a vast majority of hot runner molds have restrictive gates, there are additional options available. These options include valve gates and edge gates.

# 2 Rheology and Melt Flow in an Injection Mold

This chapter will present both a foundation in melt rheology and flow of plastics in a mold. Rheology is a reasonably well established scientific field, but the science of how polymer melts flow in a mold is not so well understood. The rheology of polymer melts is quite complex and can include influences of shear, temperature, and pressure, converging and diverging flow, elastic effects, tensile viscosities, etc. As this is not a book on rheology, this chapter only provides an introductory overview of some of the issues that most molders and mold designers should understand. This foundation also ties into a number of the later chapters.

As complex as the field of rheology is, the science and understanding of polymer melt flow in a mold reaches a higher level of complexity. Essentially we have a hot molten, highly complex, fluid flowing through a cold boundary (mold), where melt laminates are simultaneously flowing while freezing. The thermal conditions of the melt are constantly changing along its flow path and through the cross sections of the flow path. There are highly complex contrasting conditions of frictional heating in highly sheared outer laminates that are in the immediate proximity of the surrounding cold mold, where the melt is nearly instantaneously freezing upon contact with the cold steel of the mold. This near instantaneous freezing is occurring at cooling rates that can be well over 1000 °F per second. Just inside these frozen boundaries is the highest sheared region where studies have indicated melt temperatures can approach 1000 °F and several hundred degrees hotter than the melt in the middle of a flow channel such as a runner. I make these statements in this book despite the fact that there is still no technology that exists today that can measure the temperature variations that exist in a flowing melt stream, i. e. they cannot be proven true or false. These statements regarding temperature are based on simulation, mathematical modeling, fundamental laws of physics, and evidence of the impact on downstream flow channels and parts molded from these materials. Much like in the field of astronomy, we have not yet seen a black hole in space, but we know of their existence due their influence on their surroundings. Some of the issues and studies related to flow in a mold are discussed throughout this book.

The field of rheology can be defined as the study of deformation and flow of more complex fluids such as non-Newtonian polymers, pastes, suspensions, and foods. Whereas fluid mechanics would be the study of simpler fluids such as water, most oils, and air.

The earlier portion of this chapter (Sections 2.1 through 2.5) will focus on the main aspects of the rheology of plastic materials, and how important these aspects are to the process of plastic materials. This includes:

- How to distinguish between laminar flow and turbulent flow
- Calculating Reynolds number

- Fountain flow
- Viscosity of plastic materials
- Factors affecting viscosity
- Common viscosity models
- Melt compressibility
- Melt flow characteristics
- Calculating viscosity

## 2.1 Laminar vs. Turbulent Flow

Owing to the relatively high viscosity of commercial polymers, it is generally expected that flow of a polymer melt during injection molding is laminar. This is true even in the case when melt is passing through small restrictive pinpoint gates. As a result of this laminar flow behavior, processes such as co-injection are made possible.

Turbulent flow is the condition where the fluid in a channel is swirling and mixing. This condition is highly desirable for a coolant in the cooling channels of a mold in order to increase the efficiency of heat transfer from the mold to the coolant. In contrast to this is laminar flow where the fluid is flowing in distinct laminates, or layers, and does not mix. Whether flow is turbulent or laminar is a function of the viscosity of the fluid and its velocity. This can be easily determined by calculating the Reynolds number (Re#).

$$\text{Re\#} = \frac{\text{velocity} \times \text{diameter}}{\text{kinematic viscosity}} \tag{2.1}$$

Where:

$$\text{kinematic viscosity} = \frac{\text{dynamic viscosity}}{\text{melt density}} \tag{2.2}$$

$$\text{velocity} = \frac{\text{flow rate}}{\text{area}} \tag{2.3}$$

Turbulence has been found to begin at a Reynolds number of 2300 and the transition to fully developed turbulence occurs at 4000. As highly turbulent flow of water in a mold’s cooling system is considered ideal to achieve the best heat transfer, it is recommended that when designing the cooling system a Re# of around 10,000 should be targeted. This is not only to assure that turbulence exists, but also that a high level of turbulence is present in order to optimize heat extraction.

The Reynolds number calculated for most polymer melts during injection molding is much lower. In most cases the Reynolds number through even small restrictive gates is less than 10. Therefore it should be expected that flow of commercial thermoplastic polymers through an injection mold's sprue, gates, and cavity is always laminar. Although the term turbulence is often incorrectly used to describe the cause of flaws in injection molded parts, it should never actually exist. An example of calculating the Reynolds number for an ABS resin flowing through a small 1 mm diameter gate is provided in the following:

**Example:**

Given is a four-cavity hot runner mold with 1 mm diameter gates. Each cavity has a volume of 8 $cm^3$. The molding machine injects material at a rate of 32 $cm^3/s$. This results in a fill time of 1 second/cavity and a flow rate through each gate of 8 $cm^3/s$.

Shear rate through the gates is:

$$\dot{\gamma} = \frac{32\,Q}{\pi d^3} = \frac{32 \times 8\,\text{cm}^3\,/\,\text{s}}{\pi \times 0.1^3} = 81{,}528\,\text{s}^{-1} \tag{2.4}$$

This is a rather high shear rate for most materials.

- Flow rate/gate = 8.0 $cm^3/s$ (8.0 × $10^{-6}$ $m^3/s$)
- Diameter of each gate = 1.0 mm (0.0010 m)
- Cross-sectional area of each gate = 0.783 $mm^2$ (7.83 × $10^{-7}$ $m^2$)
- Dynamic viscosity = 8 Pa-s = 8 kg/m-s

$$\text{Gate velocity} = \frac{8.0 \times 10^{-6}\ \text{m}^3\,/\,\text{s}}{7.83 \times 10^{-7}\,\text{m}^2} = 10.22\ \text{m/s}$$

$$\text{Kinematic viscosity} = \frac{8\ \text{kg/m} \times \text{s}}{890\ \text{kg/m}^3} = 0.008989\,\text{m}^2\,/\text{s}$$

$$\text{Re\#} = \frac{10.22\ \text{m/s} \times 0.001\,\text{m}}{0.008989\ \text{m}^2\,/\text{s}} = 1.14$$

This value for the Reynolds Number is a small fraction of the 2300 required for turbulence to occur.