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SUMMARY

Continuous processing of viscous and particulate foods in heat exchangers is receiving increased attention, as the market for aseptic products grows. Understanding of the flow characteristics of viscous food products is important for the design and control of the process. The flow characteristics are complex and dependent not only on the type of food and the temperature, but also on the methods for and duration of the pre-treatment and heat processing.

For low viscosity foods, processing in plate and tubular heat exchangers is done under turbulent flow conditions. For high viscosity foods, turbulent flow is difficult to achieve, due to large drops in pressure and high shear stress in the products which restricts the use of plate and tubular heat exchangers. Instead, scraped surface heat exchangers are used. This equipment has a rotating inner cylinder which brings about vigorous mixing of the viscous liquid and scraper blades which remove food material that builds up on the heat transfer surfaces. The complex flow properties of viscous foods must also be considered in the selection of length of the holding tube connecting the scraped surface heat exchangers used for heating and cooling in aseptic processing systems.

If particles are added to the liquid, the flow and the heat transfer of these particles must also be taken into account. Separation of the particles from the liquid during processing must be avoided. To control the microbiological safety of the process, the speed of the fastest moving particle compared to the average fluid velocity must be known, as must the required time for the heat to be transferred to the centre of the particles.

INTRODUCTION

Extensive industrial use of aseptic processing and packaging is found in thermal processing of low-viscosity foods, such as milk and fruit juices. Much of the research and development carried out today are concentrated on applying aseptic processing to high-viscosity foods and foods containing particles. The major driving forces behind this development are shown in Table 1.

Table 1. Benefits of aseptic processing and packaging

- Better food quality (HTST/UHT)
- Reduced packaging and total costs
- New package/product opportunities

The possibilities and limitations with conventional heat exchanger equipment for processing of viscous and particle-containing foods are discussed in this presentation. Since the differences in flow behaviour of low-viscosity fluid foods, such as milk and fruit juices, and of high viscosity foods, such as soup and sauces, greatly influence the selection and operation of the processing equipment, the rheological properties of high viscosity foods are described initially. The possibility to obtain the desired operating conditions for the processing of high-viscosity food is then discussed for plate (PHE), tubular (THE) and scraped surface heat exchangers (SSHE), and for tubular holding tubes, used especially in SSHE systems.

Addition of particles to the fluid food further complicates the operation and the control of the process. The flow of the particles in relation to the fluid would ideally be controlled so that the particles are uniformly distributed in the fluid food. Factors that influence the particle suspension are discussed and some experimental results reviewed. Furthermore, the heat transfer to and inside the particle greatly influences the processing time needed for attaining sterility inside the particles. The influence of some important processing parameters on sterilization safety and product quality is shown.

HIGH VISCOSITY FLUID FOODS

Flow behaviour of viscous foods

When viscous food is processed the flow behaviour of the food becomes much more complex, compared to milk and low-viscosity fluids. The viscosity primarily defined for so called Newtonian fluids as the constant ratio between the shear stress (τ) and the shear rate ($\dot{\gamma}$), is an important product property, influencing the flow rate, the velocity profile and the pressure drop in the processing equipment.

Viscous foods, such as soups and sauces, are built up of complex food macromolecules such as polysaccharides and proteins. For these foods the viscosity is not a true constant, but varies with the processing factors, such as the rate of shear. This is expressed by the so-called power law equation for non-Newtonian food fluids, as illustrated in Figure 1.

For starch solutions, often the major ingredient giving viscosity to soups and sauces, the intensity and length of pretreatment or processing affect the viscosity. The time and temperature during heating, holding and cooling determine the degree of swelling of the starches and also influence starch retrogradation. In Figure 2, the shear stress versus the shear rate plots from viscosity measurements of three commercial starch solutions illustrate the complex flow behaviour. At high concentrations, viscosity is lost during the high-shear part of the measurements, while at lower concentrations the viscosity is constant or increases slightly during the measurements.

EQUIPMENT CONSIDERATIONS

Pressure drop

The result of the complex flow behaviour can be illustrated by the relationship between the pressure drop, the flow rate and the flow behaviour index. For non-Newtonian fluids, the Hagen-Poiseuille law gives the pressure drop per unit of length as:

$$\Delta p/L \sim Q^n / R^{3n+1}$$

where Q is the volumetric flow rate and R the radius.

Thus, the linear relationship between the pressure drop and the flow rate for low-viscosity food, which is often used for process monitoring and control, is replaced by a more difficult-to-handle relationship for high viscosity foods, where n often is less than 1, (Rao, 1986).

Plate heat exchangers (PHE)

Plate heat exchangers are built up of a large number of thin stainless steel plates. Heat is transferred from a warm fluid on one side of the plate to a colder fluid on the other side of the plate. The flow channel between the plates has a thickness of one to a few millimeters, controlled by rubber gaskets which also control the flow from one plate to another. The plates have different corrugations to promote turbulent flow. High-energy efficiency is an important characteristic of plate heat exchangers. By having a large number of plates, heat regeneration of more than 90 % can be attained in low-viscosity applications.

When the viscosity increases, the pressure drop in the flow channels also increases. By widening the channel, the pressure drop can be reduced. However, to maintain turbulence, the flow rate must be increased, which requires larger and more powerful pumps. The increased shear thus obtained may damage shear-sensitive viscous products, especially those containing solid or fibrous particles. In addition, more viscous products often give rise more easily to fouling on the heat transfer surfaces, thereby shortening the production time between cleaning.

The practical, maximum pressure drop in PHEs is between 1 and 2 MPa (or 10 to 20 bar) depending on the design and on productivity considerations. This often means that products with apparent viscosities above 0.05-0.1 Pa s (500 - 1000 cP) cannot be processed efficiently in PHEs. For viscous food applications, PHEs are only used in the high temperature section, where the fluid viscosity is relatively low.

Tubular heat exchangers (THEs)

Several different types of tubular heat exchangers are available. The shell-and-tube type consists of a number of thin tubes contained inside a larger tube or box; the shell. The food is pumped through the thin tubes at high flow rates in turbulent flow. As shown in Figure 3, this means that the maximum fluid velocity in isothermal flow is only slightly higher than the average velocity. For more viscous fluid foods, it is difficult to obtain turbulent flow and laminar flow conditions prevail. For Newtonian fluids where the power law exponent $n=1$, the ratio between the average and the maximum fluid velocity is 0.5, (as shown in Figure 3). For non-Newtonian fluids, where $n < 1$ the ratio is closer to 1. This is favourable to the quality of the treated foods.

The velocity of the fastest-moving fluid element determines the safety of the process. The time a possible microorganism spends in this fluid element and the temperature it is exposed to, determine the sterilization efficiency of the process. The average velocity is important to the overall food quality. To avoid over-processing, the ratio of the maximum to the average fluid velocities should be as close to 1 as possible. This is called piston or plug flow, which is the flow regime often desired in continuous processing.

The temperature dependence of the viscosity also influences the flow profiles in THEs, so that the flow rate at the centre is higher in the cooling section than in the heating section, compared to isothermal flow, see Figure 4.

The pressure drop in shell-and-tube THEs is high, with maximum presssures of 5 - 6 MPa (50 - 60 bar). These high pressure drops require the use of homogenizers or multiple stage pumps which, of course, restricts the area of application to low to medium-viscosity foods which are not damaged in these pumps.

Another type of THEs more often used for viscous and particle-containing foods is the concentric tube type. In this type of THEs the fluid is transported in two or more cylindrical, concentric annuli and sometimes also in the central tube. The distance between the tubes can be made large enough to allow for transport of moderate-size particles. Many different designs exist, including corrugated tubes which promote turbulence, and concentric tubes in cylindrical bundles where the centrifugal forces also influence the flow.

Scaped surface heat exchanger (SSHE)

For high-viscosity foods, especially those which coagulate or gel, fouling on the heat transfer surfaces may be a serious problem. For such products, scraped surface heat exchangers are used.

The scraped surface heat exchanger consists of a concentric tube, the inner rotor of which is equipped with scrapers preventing material from building up on the heat transfer surface. The inner rotor also creates rotational flow and at sufficiently high rotation speeds, so-called Taylor vortex flow prevails. This flow condition means that vigourous mixing is created inside the scraped surface heat exchanger by small toroidal vortices between the rotor and the stator; see Figure 5.

The Taylor vortex flow condition in the scraped surface heat exchanger is fairly equivalent to plug or pistol flow, which is the desired operating condition in most cases. In addition to the rotational flow, other factors such as axial flow rate and, of course, viscosity influence the area of the best operating conditions in a scraped surface heat exchanger. Under laminar flow conditions, channelling effects may develop with large temperature variations in the radial direction of the flow; see Figure 5.

Foods with very high viscosity can be treated in SSHEs. In aseptic processing systems, SSHEs are the most frequently used heat exchanger for heating and especially for cooling of viscous and particle containing foods. Circular tubes connecting the heating and cooling SSHEs are used as holding sections, in which the product is held at the desired sterilization temperature for a given length of time. The length of time is determined by the flow conditions during laminar flow in tubes, as described above. Traditionally, a relationship of 0.5 between the average and the maximum flow velocity is used. In most situations this gives a conservative, i.e. safe, estimate of the sterilization effect in the holding tube. However, with complex flow behavior, as in the case of the "-" measurement in Figure 2, the ratio may even be greater than 1, resulting in a lower sterilization value than what could be expected from the traditional calculation.

FOODS WITH PARTICLES

Flow of solid particles in fluid tube flow

Addition of particles to the viscous food component means that the flow of the particles in the relation to the fluid food also has to be considered, as well as the heat transfer from the liquid to the particle and the heat conduction inside the particles to the food centre. The sterility of the system is determined both by the flow velocity of the fastest moving particles and the time needed for the heat transfer at the slowest point in the particle. The quality, however, depends on the integrated evaluation of the influence of time and temperature on all the different particles and the liquid. Sterility considerations are, of course, always more important than quality consideration.

Particle flow

During particle flow, it is important to avoid the particles from separating from the liquid flow. The forces of gravity caused by the differences in density between the particles and the fluid must be balanced by drag forces preventing settling or flotation of the particles. In some situations, centrifugal forces will also act on the particles. When the forces of gravity and the drag forces are in balance the terminal settling velocity is attained. This velocity equals the axial flow rate that should be exceeded to reach homogeneous two-phase flow.

However, for particles larger than 1 mm, the theoretical terminal settling velocity is seldom reached. For larger particles, the flow is often in the so-called transition zone, where, due to gravity, the heavy particles accumulate in the lower parts of the tube flow. If the axial flow velocity is further reduced, particles will begin to settle at the bottom of the tube and a moving bed will develop at the bottom wall. This situation must be avoided, as it leads to complete loss of control of the flow of the particles.

The drag forces are dependent on the viscosity of the fluid, and higher fluid viscosity may contribute to maintaining the particles in suspension.

In the practical situation, many factors contribute to lowering the terminal settling velocity and thus to maintain also larger particles in suspension. One such factor is the deviation from sphericity of the particles. Long and thin particles are more easily kept in suspension than spherical particles. At high particle concentrations, particle-to-particle and wall-to-particle interactions also lower the terminal settling velocity, thus helping to maintain particles in suspension.

The motion of particles in the tube is among other factors influenced by the so-called Magnus' lift force. Particles subjected to differences in fluid shear forces, such as in the flow profile in a tube, rotate and this rotation results in a radial force being applied to the particles propelling them towards the centre line of the tube. However, in experiments concentration of the particles to a ring formed part of the tube flow has been found, (Sastry and Zuritz, 1987).

In studies of particle residence time in flow of water and sugar solutions, Nesaratnam and Gaze (1987) found that particles can travel slightly faster than the average fluid velocity (see Figure 6). This can be explained by the concentration of particles towards the centre line of the fluid flow, according to the radial transport.

Addition of particles to the flow also affects the viscosity of the two-phase fluid. Normally, the viscosity increases with higher particle concentration. It should also be noted that for incompressible solids, the solid fraction of the two-phase fluid is limited to less than 60% for most particle sizes, and in many industrial situations 40 % solids is a practical limit.

Particle flow in SSHEs

In particle flow in SSHEs, plug flow should be aimed at by selection of processing conditions characterized by Taylor vortex flow. Defriese and Taeymans (1987) have shown that at high rotational speed and for high-viscosity fluids, the ratio of the mean residence time of the particles to the mean residence time of the fluid is slightly lower than unity. This indicates that there is some axial mixing of the particles in the SSHE, but that the particles essentially follow the fluid flow.

Particle heat transfer

In ensuring the safety of the aseptic process, we also need to consider the heat transfer from the fluid to the particles and inside the particle. In most aseptic processing systems, the residence time of the particles in the scraped surface heat exchanger used for heating and cooling is disregarded in the calculation of sterilization values. The holding time for the particles in the holding tube is long, due to the slow heat conduction from the surface to the centre of the particles. The particles will also be over-processed because of the traditional flow assumption of laminar Newtonian fluid flow, explained above.

With these conservative safety considerations severe over-processing of particles may occur and the potential advantages of aseptic processing of foods may be lost. The quality may even be inferior to that achieved by good traditional canning, which entails a smaller risk of quality defects due to mechanical damage, (Åström et al., 1988).

Computer based calculations have shown the influence of operation parameters, such as flow profiles in the holding tube and in the SSHEs, on holding tube length, requirements (Sastry, 1986; Hegg and Karlsson, 1987). The latter authors also included the cook-value of the particle and of the fluid as indicators of food quality resulting from the thermal process. Åström et al. (1988) illustrated the effect of different flow profiles on holding tube length requirements and the resulting cook-values, see Table 2.

Table 2. Holding tube length and average cook values for sterilization of 10 mm particles. In the aseptic system, plug flow is assumed to prevail in the SSHEs and laminar flow in the holding tube. Sterility was calculated for the fastest moving particle (according to Åström et al.,1988)

Sterilization temperature,^{o}C	Holding tube length	Cook-value in particle	Cook-value in fluid
135	X	28	33
130	4X	42	45
125	20X	79	81

To determine the heat transfer to the particles, the surface heat transfer coefficient must be known. When there is no relative movement between particle and fluid, the heat transfer coefficient may be calculated as follows:

$$Nu = \alpha \cdot d / \lambda = 2$$

This gives a very conservative and safe estimate of the heat transfer coefficient, as some particle movement, e.g. rotation, can be expected. However, even lower experimentally determined values of α have recently been published (Chandarana and Wheaton, 1988).

CONCLUDING REMARKS

In this presentation I have tried to point out the important differences between processing of high-viscosity, particle-containing foods and low-viscosity foods, such as milk and fruit juices. Although traditional heat exchanger equipment may be used, great care and precaution must be taken when switching to processing of more viscous food fluids. The flow properties of viscous foods are complex and greatly influenced both by product and processing parameters. The selection of heat transfer equipment and the best operating conditions for these also affect the complexity of the flow behaviour of the viscous foods.

The need to control both the flow and the heat transfer of particles further complicates the design and control of the continuous processing of particle-containing foods. Processing of foods containing particles require strict control of the flow of the particles in relation to the fluid. The heat transfer to and inside the particles must also be precisely controlled. This complicates the control of the safety of the process and the possibility of improving the quality of the aseptic products, initially mentioned as one of the benefits and advantages of aseptic processing and packaging.

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FIGURES

NON-NEWTONIAN FOOD FLUIDS

$\tau = K \cdot \dot{\gamma}^n$ (Power law equation)

τ = shear stress

$\dot{\gamma}$ = shear rate

K = consistency index

n = flow behavior index

Examples	K	n
Milk	0.021	1.0
Corn syrup	0.05	1.0
Honey	6.2	1.0
Starch solution (5% DS)	13.0	0.57
Tomato paste (30% DS)	18.7	0.40
Apple sauce (11.5% DS)	12.7	0.30

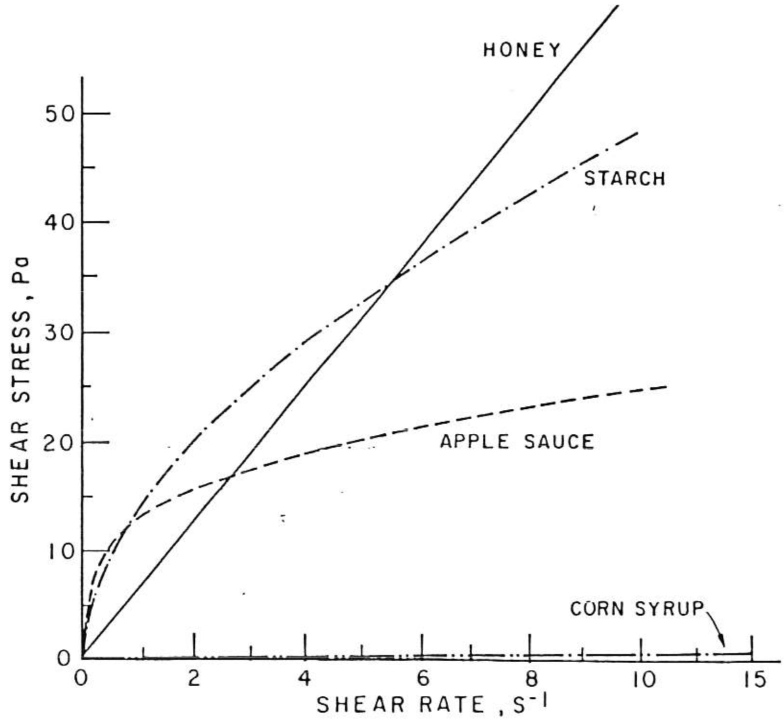

Figure 1. Some examples of non-Newtonian food fluids and the power law expression for such fluids.

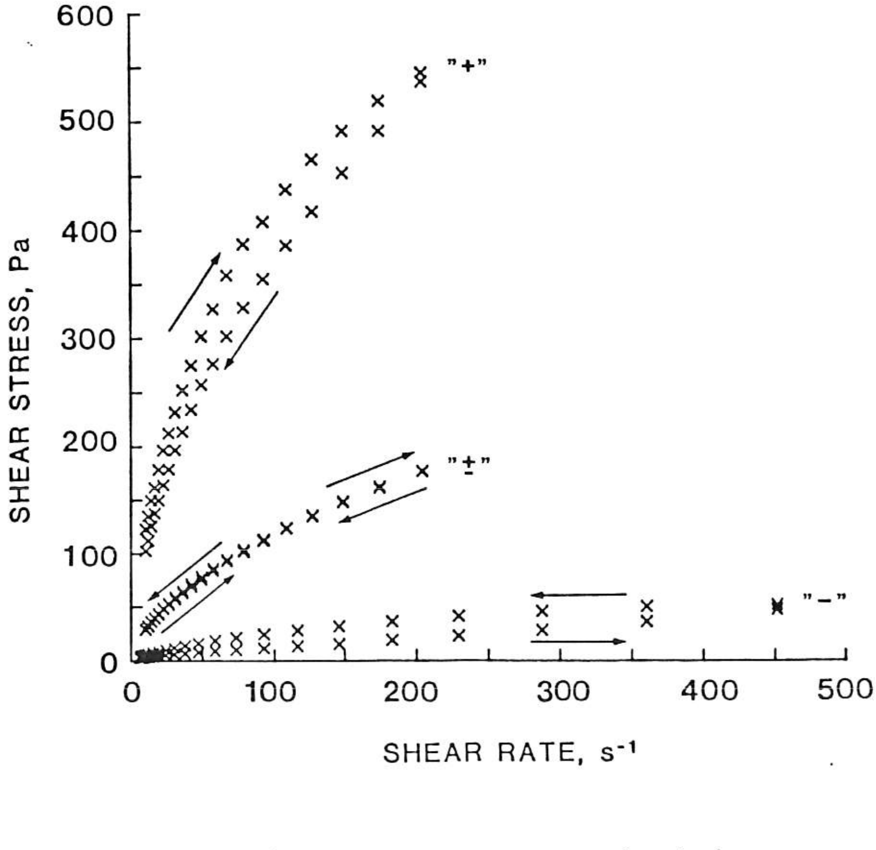

Figure 2. Examples of viscosity measurements on starch solutions.
"+" represents a 10 % starch solution subjected to high shear treatment before measurement
"+-" represents a 8 % starch solution subjected to low shear in a SSHE before measurement
"-" represents a 3 % starch solution subjected to high shear treatment before measurement (according to Härröd, 1986b)

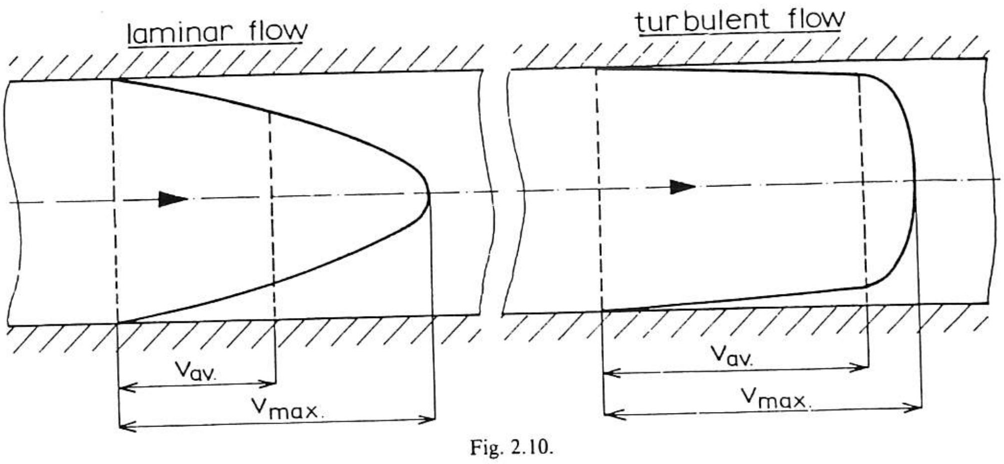

Fig. 2.10.

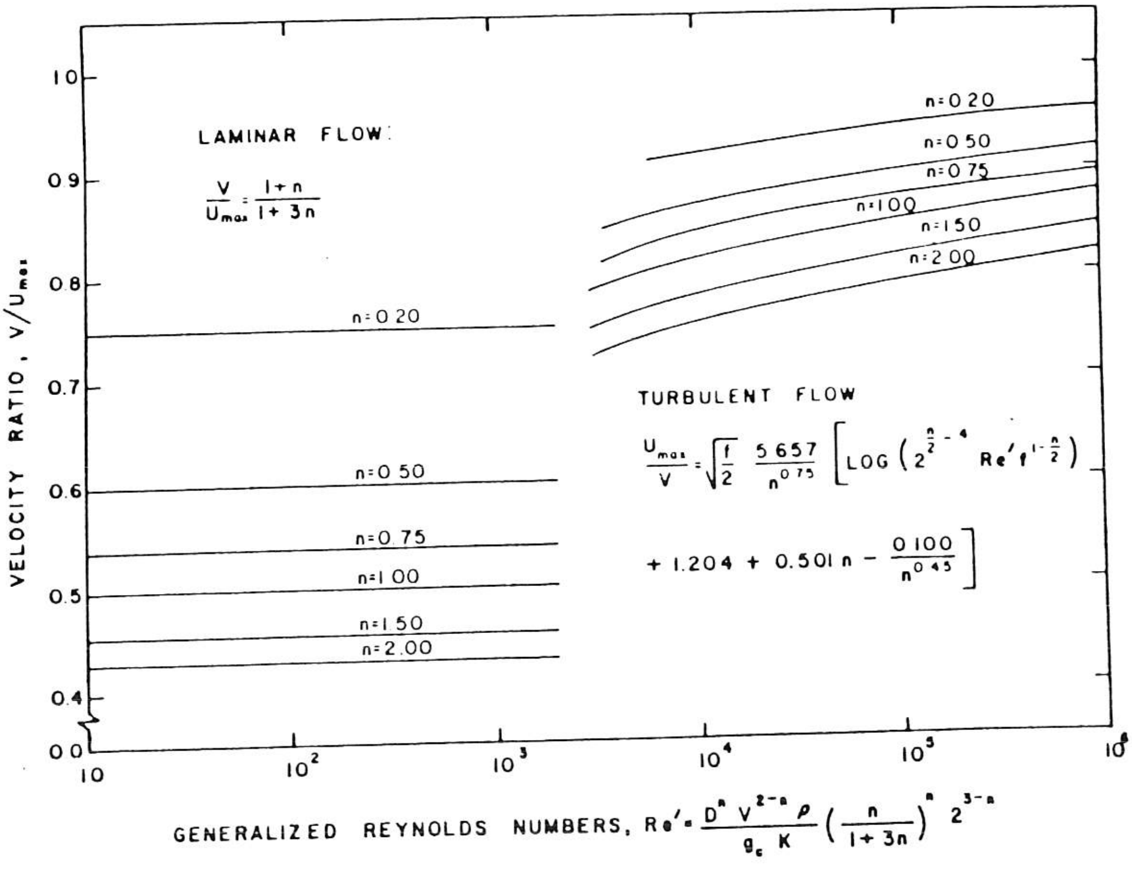

Figure 3. Velocity profiles and velocity ratios as a function of the generalized Reynolds number for power law fluids, where n=1 represents Newtonian fluids (Palmer and Jones 1976).

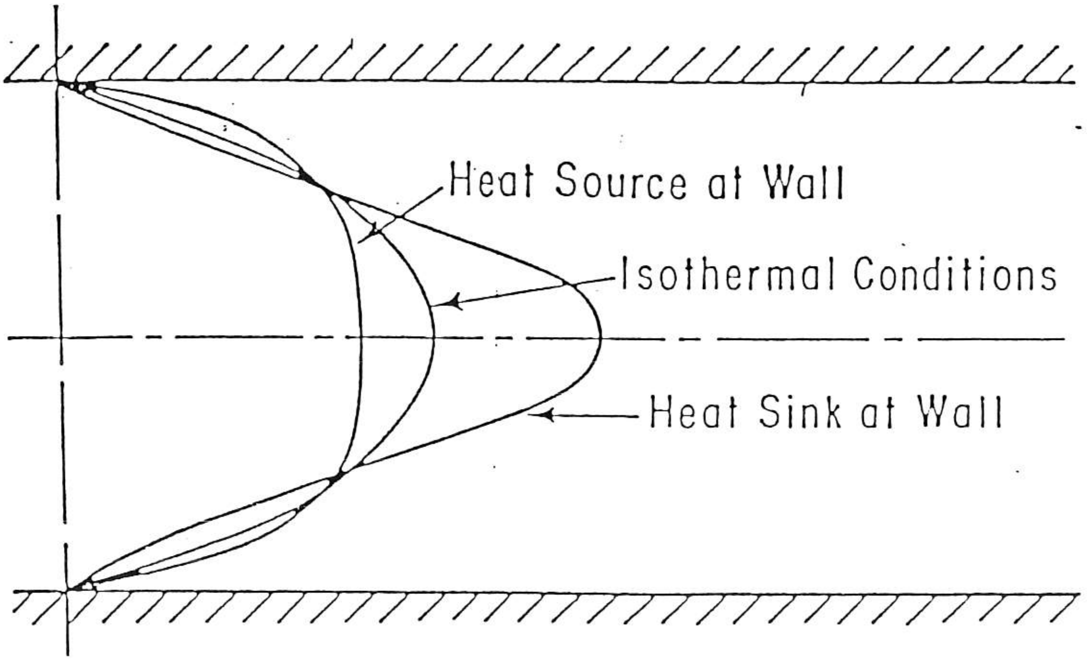

Figure 4. Velocity profile in laminar tube flow and the effect of heating or cooling at tube wall on the velocity profile (Simpson and Williams, 1974).

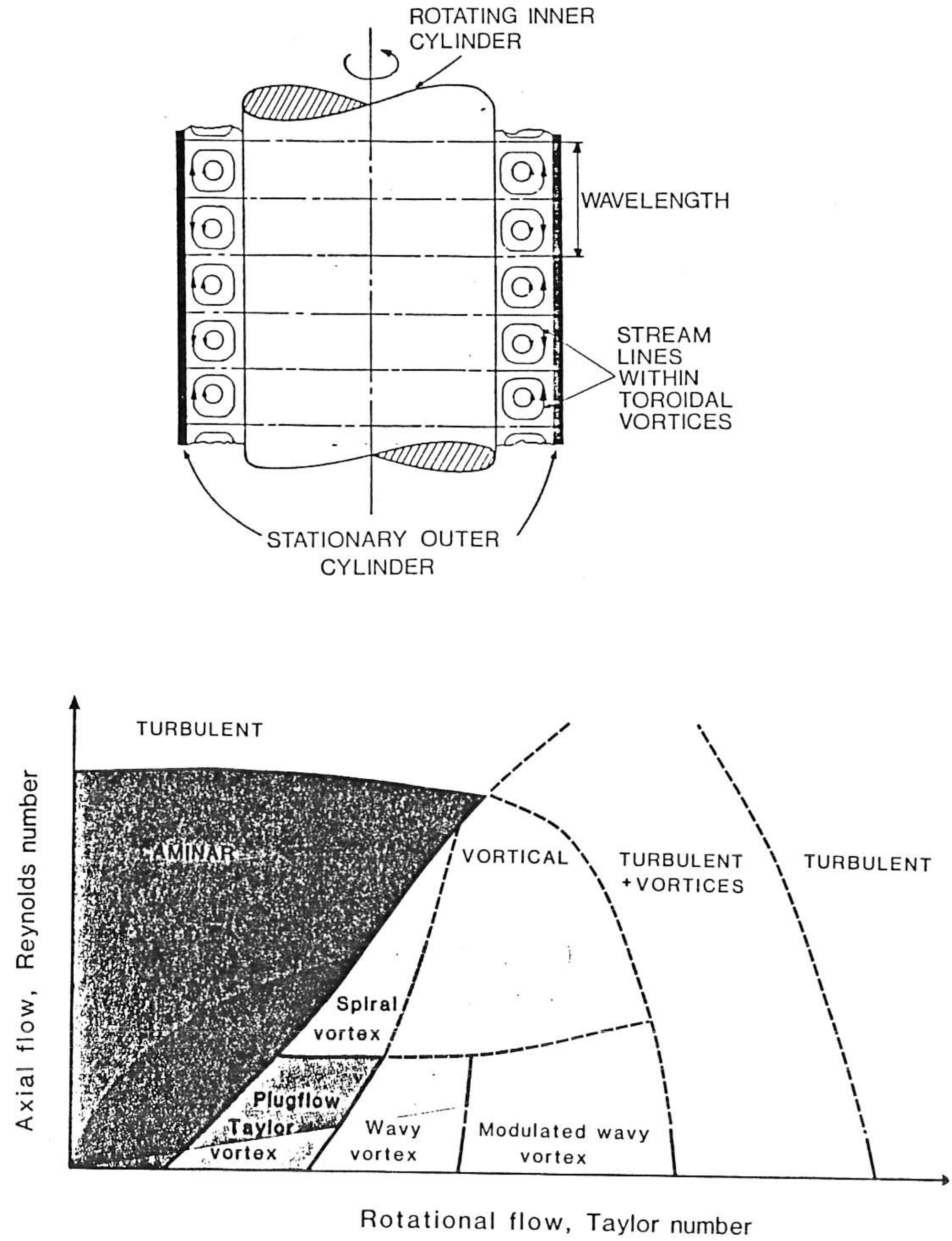

Figure 5. The Taylor vortex flow in a SSHE with rotating inner cylinder and the different flow regimes and their dependence on the rotational and axial flow, (after Härröd, 1986a)

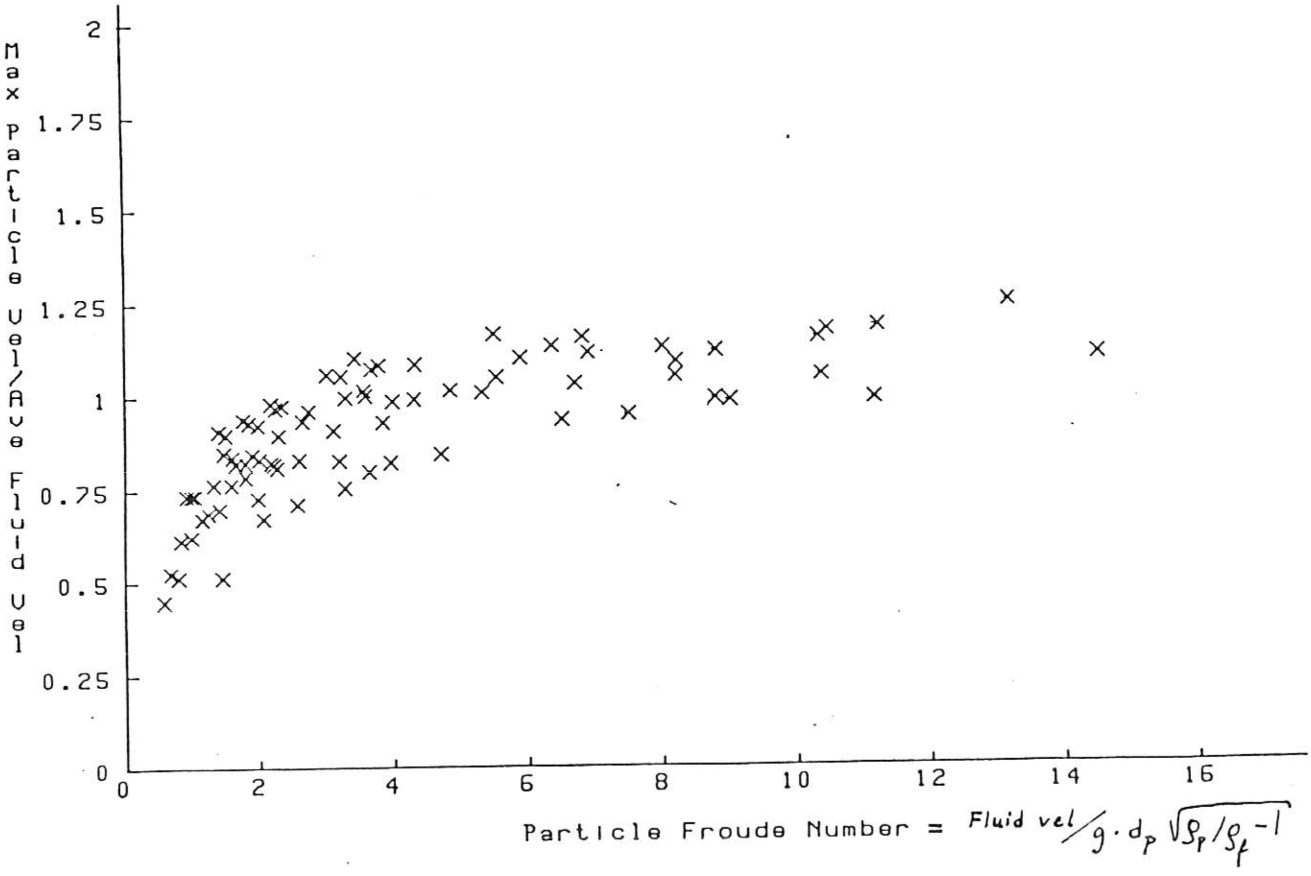

Figure 6. Maximum particle velocity over the average fluid velocity as a function of the particle Froude number (Nesaratnam and Gaze, 1987)