SENSOR TIP OPTIMIZATION FOR A THERMAL ANEMOMETER FOR DETERMINING CONVECTION INTENSITY IN QUENCH BATHS

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Abstract

Due to the occurrence of complex fluid flow patterns in a quench tank which will significantly impact hardening results, it is important to develop a compact flow measuring device. A typical quench process involves immersion of austenitized steel into a quench bath which affects the circulation of the fluid and results in non-uniform flow and thermal striations in the quenchant. This non-uniformity of fluid flow patterns therefore results in variations of heat transfer and subsequent inconsistent hardening of the parts. In this paper, the systematic optimization of the tip of a thermal anemometer used to measure flow rates in a quench tank are reviewed.

Introduction

The success of a quenching process is dependent on heat transfer during different phases of cooling, particularly during an immersion quenching process. It is well known that the overall cooling process may be affected by agitation, particularly localized flow rate variation, and in the case of aqueous polymer quenchants, bath temperature. Quenching media such as those based on petroleum oils or aqueous polymer solutions may also be significantly impacted by fluid degradation and contamination. Therefore to avoid the undesirable consequences of these effects and to provide adequate control of the quenching process, it is important to be able to characterize the overall heat transfer process in the quench tank during the quenching process.

Of these different variables, one of the most challenging (and most important) is the determination of localized flow rate variation in the tank and throughout the load. This will necessitate the development of a flow measuring probe to detect localized variations in flow and potentially permit subsequent adjustment of the heat transfer properties of the quenchant to obtain the desired metallurgical results.

To address this problem, a project was undertaken to design a flow sensing thermal anemometer. This report describes the effect of measuring tip geometry on the measurement of fluid flow rates.

Discussion

A. Principles of Operation

To define cooling power in production quenching tanks, the use of linear fluid velocity is not helpful because flow direction and twist are not defined. Full definition of cooling power requires measurement of cooling behavior of the part at different positions during the quenching process as shown in Figure 1. For example, determination of cooling power inside of a ring or a basket of small parts may be determined at different positions around the parts using a probe such as that illustrated in Figure 2. Applying these principles, the probe illustrated in Figure 3 was developed to record data that represents the relationship between the flow velocity in a quench bath and the heating power applied to the heat source of the probe.

Figure 1 - Schematic of an agitated industrial quenching tank with different kinds of parts and the probe used to quantify the quenching power at different locations in the tank.
A probe similar to the probe illustrated in Figure 2 has recently been developed.[1, 2, 3] This probe measures heat flux from the part to the surrounding quenchant with an unknown flow velocity and an unknown turbulence or twist. The probe geometry has been designed to minimize dependence on flow direction and still be highly sensitive to agitation. The body of the probe has a freely defined temperature $T_{\text{probe}}$ that fulfills the conditions:

$$T_{\text{Leidenfrost}} > T_{\text{probe}} > T_{\text{bath}};$$  \hspace{1cm} (1)

and

$$T_{\text{probe}} = \text{constant}$$  \hspace{1cm} (2)

by variation of conducted energy. This probe permits measurements of delivered energy according to the equation:

$$E_{\text{con}} - E_{\text{del.}} = \text{constant}$$  \hspace{1cm} (3)

Because the delivered energy $E_{\text{del}}$ depends on chemical qualities of the bath, $T_{\text{bath}}$ and agitation (composed from flow rate ($v$) and twist) is provided, a value for the “quality of agitation” or cooling power using dimensionless flow. With this information, two other parameters may be determined:

$$E_{\text{con}} = C \cdot \text{“quality of agitation”},$$  \hspace{1cm} (4)

where $C$ contains the thermal properties of the probe including $T_{\text{probe}}$, the chemical properties of the bath, $T_{\text{bath}}$ and $E_{\text{del}}$. The change of the probe’s temperature until achieving a stationary condition according to equation 4 is schematically given in Figure 4. The temperature of the probe ($T_{\text{probe}}$) decreases upon submersion of the probe in the quenching bath to a defined position and then increases by automatic variation of $E_{\text{con}}$ until reaching the initial temperature of the probe ($T_{\text{probe}}$). Once the parameters of the probe are defined, correlation between $E_{\text{con}}$, $T_{\text{bath}}$ and quality of agitation may be determined. Measurement accuracy increases with increasing $T_{\text{probe}}$.

The criterion for this study was the amount of electric power consumed to maintain a defined excess temperature at flow rates of 0.3 – 2.6 m/s. The absolute consumption of electrical energy at the maximum flow rate and the rise in the power curve over the entire flow range was determined for each tip geometry design studied. To optimize probe behavior, various modifications were made to the tip geometry and to the probe design. The degree to which the tip geometry was dependent on the flow direction of the fluid was tested. This report summarizes the results of this work.

If both heat flux density (due to agitation of the fluid) and flow velocity are determined, comparative measurements may be performed in the production quenching tank and also in a laboratory quenching bath with identical fluid composition, bath temperature, and well defined. Heat flux distribution in production quenching is correlated with precisely defined agitation velocities in laboratory equipment. Heat flux from the probe into the fluid is influenced strongly...
by all parameters of agitation including; flow velocity, turbulence (or twist), and direction of the main flow vector versus the cooling surface. Agitation can only be precisely defined if the same kind of turbulence exists in a laboratory apparatus [4]. The affect of quenchant agitation on steel phase transformation does not require precise qualification of the agitation conditions but it is important to define the quantity of heat flux and heat transfer coefficient (α) with respect to position in the cooling part. This may be calculated using the Tprobe.

Thermal probes consisting of semiconductor resistors are suitable for the measurement of low velocities due to their high temperature coefficients and associated high output signals. The measurement sensor is heated electrically. A state of equilibrium is reached in correspondence with the cooling conditions.

The temperature of the measurement sensor present in the state of equilibrium determines the resistance. Appropriate circuitry derives a signal from this resistance, and suitable measurement technology then evaluates the signal.

Thermal methods involve heating the medium to be measured. The heat balance can then be used to calculate the mass throughput and thus the flow velocity of the medium from the amount of heating power supplied to increase the temperature of the fluid and the specific heat capacity of the fluid.

Several potential methods for heating the flow probe were examined before choosing an efficient and economical method of using a heating cartridge. A relatively large amount of heat can be generated in a very small space by these components.

Experimental

Heating cartridges consist of resistance wires installed inside a metal jacket. The wires are protected against damage by intrinsic heating by insulated ceramic fill. Heat is transferred by thermal conduction through the metal jacket to a body in contact with the flowing fluid. This relatively loss-free energy transfer permits reduction of the electric power required for the flow probe. Anemometer probe tip designs that were evaluated are illustrated in Figure 5.

![Anemometer probe tip designs](image)

**Figure 5** – Anemometer probe tip designs.
To evaluate the dynamics of the probe with respect to the heating rate of the cartridge and the flow of heat to the probe tip, a constant voltage was applied to the heating cartridge by means of a voltammeter while the changes in temperature (measured with thermocouples) at the probe tip and in the flow channel were monitored. An illustration of the apparatus used for these experiments is shown in Figure 6.

Agitation was supplied using a propeller connected to a variable speed electric motor. The propeller speed was set to a constant value that is directly proportional to the local flow velocity that was determined by means of an opto-electronic tachometer.

An electrical voltage was applied to the heating cartridge until the temperature difference between the fluid in the experimental bath and the probe tip had reached the desired value and equilibrated as displayed on the temperature-measuring instrument. The power applied to the heating element and temperature values were then recorded. Thus, at a constant temperature difference $T_{\text{probe tip}} - T_{\text{bath}}$, the value for the heating power associated with the selected rotational speed was obtained. The temperature difference was kept constant.

The power consumption behavior curves that were obtained with the different anemometer probe tips illustrated in Figure 5 using the apparatus shown in Figure 6 are provided in Figures 7 and 8.

![Figure 6](image)

Figure 6 – Illustration of the experimental flow apparatus equipped with the flow probe.

![Figure 7](image)

Figure 7 – Power consumption behavior of the probe tip versus flow rate of water as a function of: a.) temperature measurement site in the tip; b) temperature difference ($\Delta T$); c. shape of the tip; d.) orientation to the direction of flow (hemispherical tip); and e.) orientation to the direction of flow (spiral tip diffuser).
Results

On the basis of initial considerations, it was concluded that a spherical geometry would be likely to exhibit heat transfer behavior nearly independent of flow direction. However, it is impossible to construct a sensor head with the ideal perfectly spherical shape. Heat extracted from the sensor head by the flowing liquid must be supplied to the head via the shaft of the probe. The cross-section of the shaft of the sensor head must be big enough to conduct the required thermal current to the tip of the probe. These factors require a connection with the cross-section that is approximately the same as the cross-section of the spherical geometry of the measuring tip. This reduces the ideal spherical shape of the measuring tip to the geometry of a hemisphere.

To conduct preliminary experimental studies, two hemispherical sensor tips with diameters of 2.5 and 4.0 mm were produced. To suppress the heat transfer from all nonspherical surface components of the probe body, especially the area of the probe shaft, these areas were covered with thermal insulation.

Figure 9 illustrates the amount of electric power consumed by the two probes in water with a flow rate of 0.3 – 2.6 m/s. In these experiments, the direction of flow against these measuring probes was perpendicular to the axis of symmetry. The electric power consumed by the two probe geometries shows a similar pattern, but a linear dependence on flow direction is not present. As the diameter of the measuring tip increases, the electric power consumption also increases as a result of the increase in the heat-dissipating surface area of the probe tip. The two sphere diameters selected differed in their power consumption by about 0.6 W over the entire flow rate range. The consumption curves showed a satisfactory slope and were therefore deemed suitable as calibration curves for determining the flow rate in specific application experiments to be performed at a later date. The maximum amounts of power consumed were 4.0 and 4.6 W and are in a range which, if necessary can be confirmed using mobile, hand-held units. The response sensitivity of the sensor tips is good for the flow rate ranges studied.

Figure 9 – Power consumption behavior of probe tips S5 and S6 versus the flow rate of water.

The decisive disadvantage of this probe geometry is the very strong dependence of the consumed electrical power on the flow direction. One possible reason for this is the interference that the insulation around the probe shaft causes in flow surrounding the tip of the probe. It has been impossible so far to derive a clear explanation for this observation without further experimentation.
The effects of the location of the temperature measurement site in the probe body on total power consumption and on response sensitivity (dynamic behavior of the probe) were determined. These studies were conducted with tip S7 (see Figure 5) which is a hemispherical tip with a radius of 1 mm. The cross-section of the cylindrical shaft attached to the hemisphere was the same as that of the hemisphere. The probe shaft was 6 mm long and thermally insulated over its entire length. The selected temperature measurement points (M1, M2 and M3) were located at distances of 7.0, 4.5 and 2.0 mm respectively, from the tip of the probe.

The power curve for the various temperature measurement sites are shown in Figure 7. The temperature differences between the measurement site in the shaft of the probe and the bath temperature was kept constant at 3 K ($\Delta T$ = 3 K). The consumed electric power shows nonlinear behavior versus the flow rate in all three measurement locations. Decreasing the distance between the temperature measurement site and the tip of the probe increases the total power considerably. This can be explained by the Fourier Law of Heat Conduction, according to which, with increasing proximity to the surface, the temperature curve shows exponential behavior with increasing temperature gradients. It is especially striking in Figure 5 that as the temperature measurement site moves from a distance of 4.5 mm away from the probe tip to a distance of 2 mm, there is a definite increase in power consumption. It could be observed simultaneously that, as the temperature measurement site moves farther away from the sensor tip, the response sensitivity (sensor dynamics) clearly decreases. From these data, a distance of 2 mm between the temperature measurement site and the sensor tip was “ideal”; that is, the probe tip satisfies certain ideal concepts with respect to dynamic response behavior and power consumption.

The power behavior at various excess temperatures was also examined using probe tip S7 (Figure 5). The amounts of electric power consumed by the probe tip to reach a certain excess temperature ($\Delta T = 1, 2, 3, 4$ and 6 K) are shown in Figure 6. The first striking feature is that, at higher flow rates, the excess temperature exhibits a fundamental effect on the total consumption of electric power; the power curve slope increases with increasing excess temperature ($\Delta T$). On the basis of these data, an excess temperature of $\Delta T = 3$ K was selected, that is, the power consumption of the probe body at high flow rates and the increase in the power curve as an whole can be considered optimum at this value.

Sensor tip geometries other than hemispherical were also studied. Figure 6 provides a comparison of the S10 hemispherical tip with the S8 conical sensor. Very different responses with both tips at high flow rates were observed for total power consumption and for the increase in the power curve. The slope of the power curve for the conical tip was more evident than that observed for the hemispherical tip and thus corresponds more closely to the “ideal” tip shape.

The dependence of the electric power consumption on flow rate is shown in Figure 6 for probe tip S10. (see Figure 5). The fluid was directed at flow angles of 90°, 75° and 60° to the axis of symmetry of the measuring probe tip. The differences with respect to the amount of power consumed as a function of flow angle is clearly evident in these curves. Significant deviations in the power behavior occur at a flow angle of 60°, whereas the power curves at 75° and 90° are nearly identical. Based on these studies, it is concluded that due to the dependence of its electric power consumption on flow direction, a hemispherical probe tip is not suitable for the determination of flow rates.

An attempt was made to reduce the dependence of the hemispherical probe tip on its orientation by the attachment of a so-called spiral diffuser (a spiral ring placed over the tip of the sensor.) The results of these power curves for the modified probe tip at flow angles of 60° and 90° is illustrated in Figure 7. These data show that different power curves are obtained, therefore, it is not possible to make the hemispherical tip independent of flow angle, even with the use of a diffuser.

A fundamental examination of the conical probe tips was also performed. Probe tip S8 (see Figure 5) was constructed with a cone angle of 90°, and the temperature measurement site in the probe shaft was located 2.0 mm from the probe tip. Figure 8 shows that electric power consumption as a function of flow rate for flow angles of 60°, 75° and 90° to the axis of probe symmetry. With this probe geometry, a slightly different power behavior was found only in the high flow rate range where the uncertainty of measurement must also be considered.

The power behavior of conical probe tips with cone angles of 60° and 120° was studied. Figure 8 shows that the power behavior of this probe tip is very dependent on flow direction. The power curve of a tip with a very blunt cone angle, 120°, and its dependence on flow direction are provided in Figure 7. For the conical tip too, it is evident that the electric power consumption is dependent on flow direction. As the flow rates increase > 1 m/s, the two power curves exhibit increasing differences between them. On the basis of this work, it is concluded that a probe body with a cone angle of 90° and with dimensions shown in Figure 5 for tip S8 can be considered to represent ideal probe geometry.

**Summary**

To optimize heat treatment performance it is necessary to minimize localized flow rate gradients in commercial quench tanks. These localized flow variations may be measured using thermal anemometry. This paper described the use of thermal anemometry to examine the power curves of different flow geometries in the flow rate range of 0.3-2.6 m/s. The performance of individual tip geometries were then evaluated on the basis of the following criteria:

- Maximum amount of electric power consumed,
- Rise of the power curve,
- Dynamic behavior of the tip and lack of dependence of the flow angle.

To improve performance with respect to the above criteria, design changes in the probe tip and body during the preliminary experimentation was performed. The following variables were found to exhibit very significant effects:

- Insulation of the probe shaft,
- Location of the temperature measurement site in the probe body,
- Geometry of the tip.
The experimental studies reported here show that the conical probe tip with a cone angle of 90° and an insulated probe shaft was the most suitable measurement tip geometry for this case. The selected probe shape performs better in this application than any of the other tested geometries and it also exhibits a power uptake which is independent of flow direction over the entire flow rate range. The probe dynamics achievable with this tip geometry the length of time that it takes to achieve a steady state temperature difference ($\Delta T = 3K$) in the probe body is excellent. Within the scope of this work, it has been demonstrated that it is possible to validate experimentally that a conical tip can be used to make reliable measurements of the localized flow rates in any industrial quenching fluid.

References


