

Development of customized thermowells for enhanced performance in temperature measurement.

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ABSTRACT

Optimization of a temperature sensor in order to strike a proportion between strength and desired static and dynamic performance in severe environments is a difficult task. Thermowells are generally used for protection of temperature sensors like RTDs & Thermocouples, from severe adverse conditions like mechanical shocks and corrosive environments. Basic thermowell design is documented in ASME PTC 19.3. It deals with design of conical thermowell only. This paper deals with the design approach adopted for various types of thermowells used in the process industry particularly in the nuclear industry wherein thermowells are custom designed to obtain better performance over conical design documented in ASME. As such for a prototype sensor, 3 different designs of thermowells have been modeled and simulation studies were performed to evaluate the performance parameters. Subsequently, a computer code has been developed for the design and intelligent selection of thermowells for nuclear applications. This paper also gives an insight for optimizing the selection procedure of thermowell, balancing hydraulic and vibration requirements against static and dynamic errors. The most prominent among static errors is conduction error commonly called immersion error; which is present whenever a temperature gradient exists between a vessel or pipe and the substance being measured. A detailed experimental study of performance parameters like accuracy, conduction error and response time of the thermowell assembly has been carried out. This paper gives deep insight into thermowell design, code compliance, errors introduced due to thermowell in temperature measurement, theoretical and experimental evaluation, simulation studies determining

drag force and pressure drop analysis and its validation through analytical correlations.

Keywords: Natural frequency, Strouhal frequency, Response Time, Accuracy, Conduction Error.

1.0 Introduction

Under many conditions met in ASME Performance Test Code (PTC), the desired accuracy in the measurement of temperature can be obtained by suitable selection, installation and correct use of temperature sensors; and by proper interpretation of the results obtained. Now, in many cases, a sensor like RTDs and thermocouples cannot be placed directly into the medium owing to the fact that the sensor might be susceptible to the nature of the medium and the extreme process conditions. Hence, thermowells are introduced which is a pressure type receptacle used for housing the sensor. Thermowell acts as the housing for temperature sensor and also allows in situ replacement. On the other hand, it introduces a thermal lag as well as errors in temperature measurement which should precisely be quantified for fail-safe operation. These are provided with suitable threads or weld joints for tight pressure attachment to a high pressure vessel or pipe.

The thermowell is however, a source of measurement error. It introduces a time lag in the temperature measurement as well as affects its accuracy. Hence, a striking balance between its strength and measurement accuracy must be posed so as to achieve the optimal design features for a particular process requirements. Till date, ASME PTC 19.3 is being referred to as the ultimate design guide for thermowells. Generally, there are 3 types of thermowells available worldwide. Out of which, ASME supports the design of Conical Thermowells

only [1]. For the rest i.e. cylindrical and customized types, there are no such codes available in the literature or industry. This paper highlights the important design features for the last two types.

2.0 Design Procedure

Thermowell failures are mainly caused by forces imposed by static pressure, steady state flow and vibration. Separate evaluations of each of the above effects were made in order to determine the limiting conditions. Thermowell designs were categorized into 3 different types in which primarily the conical configuration is based on ASME PTC 19.3. The design criteria for cylindrical (straight or uniform) thermowell are based on the fundamental principle of a cantilever beam (in the shape of a hollow cylinder) fixed at one end subjected to a load at the other. The expression for natural frequency (for a straight thermowell) of a cantilever bar with a uniform cross-section,

$$f_n = \frac{\lambda^2}{2\pi L^2} \sqrt{\frac{EI}{wA_s}} \dots (1)$$

Where, the secondary moment (also called area moment of inertia) can be calculated using the following expression,

$$I = \frac{\pi}{64} (D_2^4 - D^4) \dots (2)$$

Wake frequency: Strouhal frequency by Karman's vortex sheet [2]

$$f_w = St \cdot \frac{V}{D_A} \dots (3)$$

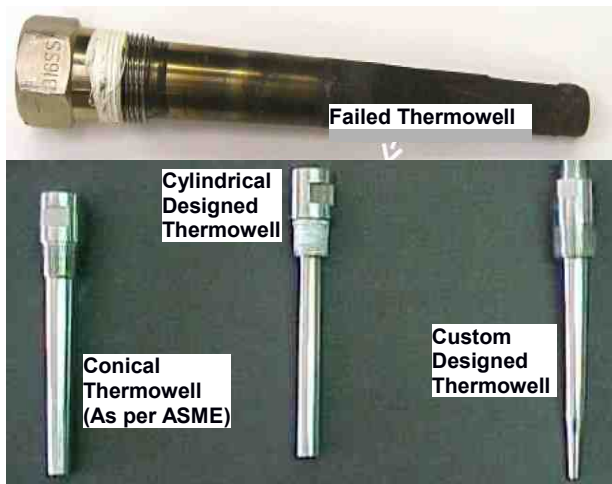


Figure 1. Types of Thermowell

In order to generate a fail-safe design, the ratio of the wake (vortex induced) frequency to the natural frequency of the thermowell should be less than a factor 0.8 [1]. Otherwise, resonance will cause high amplitude vibrations, eventually leading to thermowell failure. Also the bending stress due to velocity should be well below the maximum allowable stress of the material. These are the few important governing constraints which determine the design feasibility of a thermowell under the required process conditions.

The third type of thermowells is basically custom designed. It finds its application in the process industries, especially nuclear sector, characterized by high pressure and high temperature conditions. This design is slightly unconventional, in order to provide a best possible combination of strength as well as measurement accuracy. Customized designs are categorized into two types – B1 (used in 220MWe Indian PHWR) and B2 (used in 540MWe Indian PHWR). The B1 types are marked with smaller insertion length (also known as immersion length) as compared to B2. As far as its design is concerned, the secondary moment of inertia (i.e. area moment of inertia) term in natural frequency expression for a hollow cantilever will change owing to its non-uniform shape. Moment of inertia for complex shapes are normally found by dividing the cross section into more manageable sections, calculating the moment of inertia for each section, and combining the moments to find the total. This technique gives a weighted mean, "average" moment of inertia that is used in the standard beam equations

$$I_{av} = \frac{\sum_{i=1}^n L_i}{\sum_{i=1}^n \left(\frac{L_i}{I_i} \right)} \dots (4)$$

Accuracy in measurement can be improved by making the section lengths as small as practically feasible.

3.0 Code Development

A computer code [TEWEL] has been developed for the intelligent selection of thermowells for wider applications in nuclear industry as well as other sectors. It's a universal code for thermowell design. The

user is only required to specify the process conditions and line size in which the thermowell is desired to be installed along with the type of pipe material and insulation details. A list of candidate materials used for thermowell fabrication at high pressure & high temperature applications has been provided as a part of the program.

The output of the programs generates an optimum design with exact dimensional specifications and sizing features based on the boundary conditions.

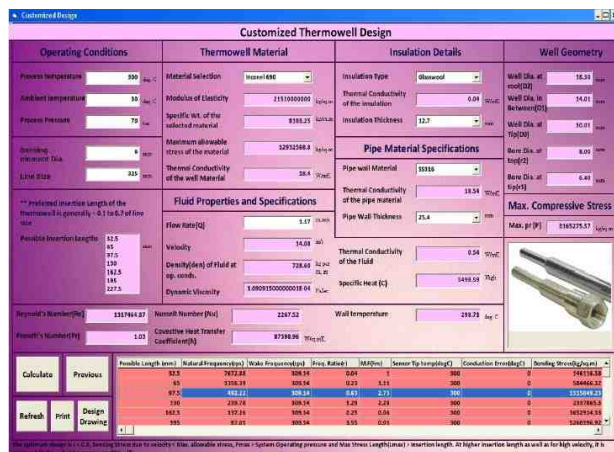


Figure 2. TEWEL Code

4.0 Sources of Error

Any temperature sensing element indicates its own temperature and, even under steady-state conditions, the temperature of the sensing element may not be that of the fluid or solid with which it is in contact. If a fluid is at rest or moving with relatively low velocity, the temperature indicated by the temperature sensing element for a steady state condition is a result of a balance of convective heat transfer between the element and the fluid, and heat transfer by conduction and radiation. Radiative loss with polished surface is low, and can generally be ignored. The major concern in this case is the *conduction error*, also known as the immersion error. It is a *static error* and is present whenever a temperature gradient exists in the temperature sensor, or in other words, any time there is a difference between the pipe wall and the flowing medium. The following relation is used with good accuracy for determining the extent of the conduction error, [1]

$$T_{sg} = T_i - \left[\frac{T_w - T_{sg}}{\cosh(mL)} \right] \dots (5)$$

In view of the above, any means of increasing the product ml will result in a reduced conduction error.

Apart from this, there is another source of error known as *dynamic errors*. It is impossible for any temperature sensor to instantaneously undergo a step-change in temperature because of the thermal capacity of the sensor itself. As per our experiments, introduction of thermowell, introduces further lag in response. A finite time interval is required for the thermowell assembly to absorb, or to dissipate, heat during a transient. Because of this, the temperature of the sensor, in general, will be out of phase with temperature of the medium being measured during a transient condition. In addition to being out of phase, it will also be different in magnitude. It is seen that the temperature error due to dynamic response becomes more significant for thermowells having long integrated time constants.

5.0 Drag Force and Pressure Drop Analysis using Computational Fluid Dynamics (CFD)

A detail study of the drag force as well as pressure drop analysis experienced by a thermowell when inserted inside a pipeline under flowing conditions has been carried out. The objective is to determine the maximum bending stress developed in the thermowell due to high flow velocity using computational fluid dynamics, followed by analytical verification. The CFD analysis has been performed using PHOENICS code, and the results obtained are validated with the existing fundamental correlation.

Modelling & Simulation

The modelling of the thermowells inserted inside a pipeline has been carried out using SOLID WORKS. A 3D domain is considered for simulation and Cartesian co-ordinate system is selected for analysis. Turbulence model is used for simulation. Convergence criteria taken for simulation are 0.1%.

The length of the pipe is taken as 1.2 m which is sufficient enough for the development of a full velocity profile. At around 0.8m on the z-direction from the start, the thermowell was inserted. In order to qualify the thermowells for nuclear environment, an extensive study has been carried out to determine the failure analysis under severe accidental conditions, such as

LOCA (Loss of Coolant Accident). A large number of models have been developed with varying line sizes and different thermowell insertion lengths for simulation purpose. The process condition was maintained at 300°C. The fluid medium was considered to be water having a density of 728.6 kg/m³. The inlet velocity was varied as per line sizes keeping a constant value of Reynolds Number. Almost 2000 iterations were carried out in order to realize a converged solution. The result conforms to the fact that, with increasing insertion length of thermowell, chances of failure are considerably higher, due high stress generation at its neck portion. Hence, an optimize design criteria can be obtained under such observations, in order to meet various process requirements.

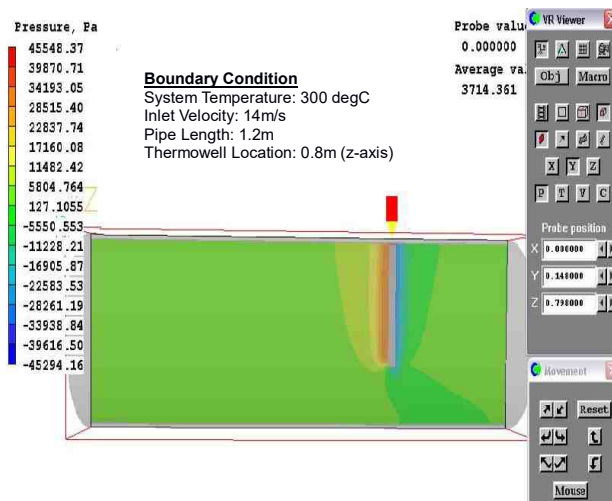


Figure 3. Pressure profile (X-Z plane) across the Thermowell

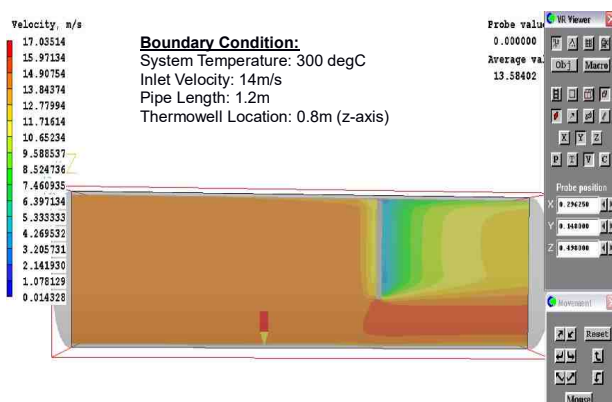


Figure 4. Velocity profile (X-Z plane) across the Thermowell

The maximum pressure drop was determined across the thermowell and the

drag force was calculated by using the correlation:

$$F = \Delta P_{\text{Max}} \cdot A \quad \dots (6)$$

Validation of CFD output with analytical correlation

The drag force F_{CFD} calculated using CFD output = 190.315 N

From the theoretical correlation for drag force expressed as

$$F = \dots (7)$$

For the flow velocity 14m/s, becomes 186.85N. The above result shows an error of only 1.85% between the simulated value of drag force and the analytical value. Considering the approximation technique used in PHOENICS, this result conforms the required validation.

Apart from this, using CFD we can infer the fluid flow behavior across the thermowell. It complemented the experimental and analytical approaches by providing an alternative cost-effective means of simulating the real conditions.

6.0 Experimentation

An experimental study has been carried out using RTD as the temperature sensor in order to determine the performance of various important parameters like response time, accuracy and conduction error.



Figure 5. Experimental Set-up

The set-up consists of a rotary bath which simulates the flowing conditions. The tests were performed at 80°C under normal atmospheric pressure conditions. Also to facilitate the achievement of actual immersion lengths, the thermowell shank was marked at regular intervals.

Response time characteristics

The ability of a temperature sensor to respond to a change in temperature is typically given in terms of its “time constants”. This is the time required for the element to change in temperature an amount equal to 63.2% of the imposed step change.

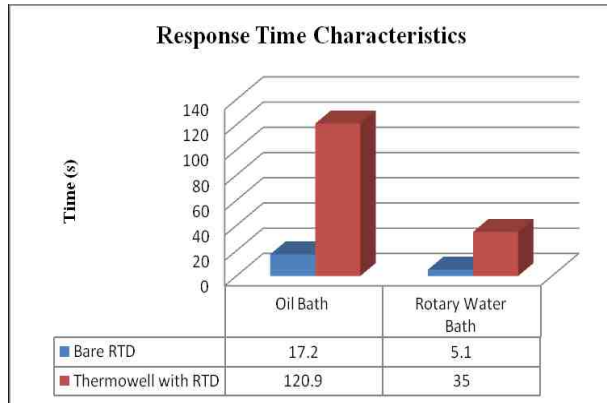


Figure 6(a). Response Time Variation in Oil Bath and Rotary Bath (RTD: 6mm OD)

This time constant varies with change in flow velocity. The experiments were carried out under both steady and flowing conditions. The graphs below confirm that the response time of a thermowell assembly is higher as compare to the bare sensor, when there is a considerable flow of the measurement medium.

Fig.6(a), shows that the insertion of a thermowell introduces an additional time lag of around 90 to 100 seconds in static condition, whereas, around 30 seconds in case of flowing conditions (3 fps); depending upon the thickness of the thermowell and flow velocity. This confirms the fact that with higher flow velocity, which results in higher heat transfer rate from the fluid to the thermowell body, the response characteristics improves drastically. The graph below Fig. 6(b), gives a complete picture of response time variation owing to different shapes, thickness of thermowells. Experiments were carried out on including two types of cylindrical thermowell of varying wall thickness as well three modified designs of B2 types.

The response time of B2 type (proposed design) is the lowest of all i.e., 65.2 seconds.

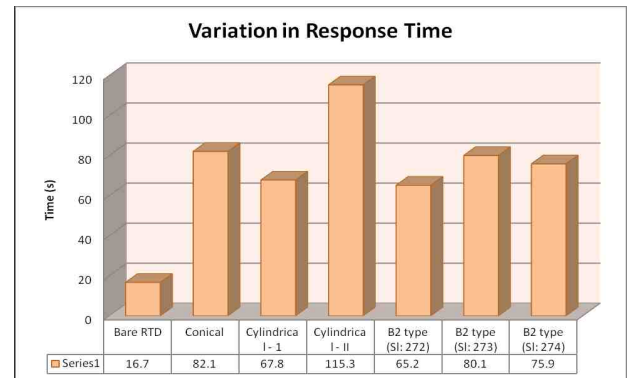


Figure 6(b). Response Time Variation for different types of thermowells (RTD: 6mm OD)

This is due to the fact that, the design thickness of the thermowell, near the sensing region is very small as compared to conical (as per ASME PTC 19.3) or cylindrical types. Its non-uniform shape imparts the required strength to withstand the process condition along with a considerable improvement on the response time issue.

Measurement Accuracy

As far as the accuracy of measurement is concerned (i.e. the degree of closeness of measured value to the true value), it has been observed that, thermowell insertion contributes a sustained measurement offset even if sufficient time interval is allowed to the sensor to reach the steady state.

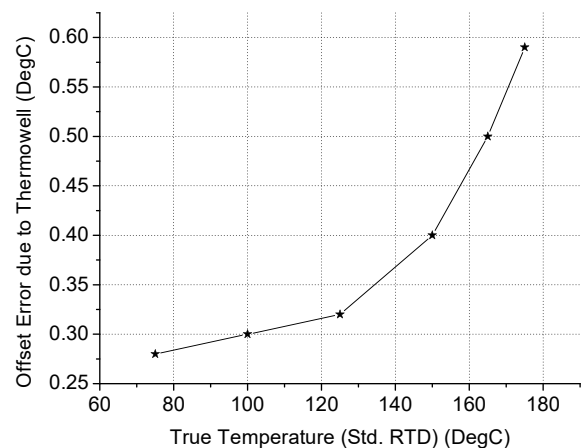


Figure 7. Accuracy Determination

The above experiment (Fig. 7) was carried out in a dry block calibrator. The result shows that, only a variation of $(0.3 \text{ to } 0.6)^{\circ}\text{C}$ was observed when temperature was increased from 75°C to 175°C .

This is associated with a steady increase of the error as we move towards higher temperature. Currently, the same experiment

is being repeated for higher range of temperature.

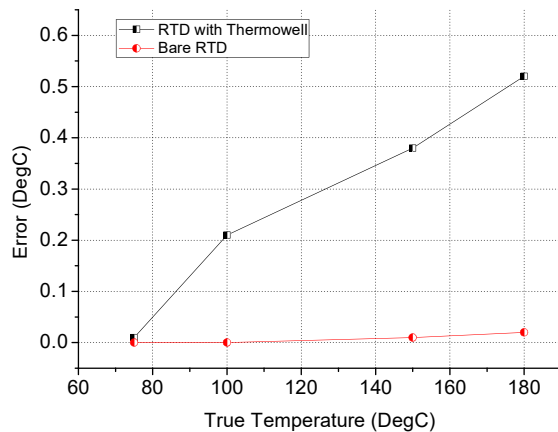


Figure 8. Effect of Thermowell on Temperature Measurement

Fig.8 demonstrates contribution of measurement error with insertion of thermowell as compared to the bare RTD sensor.

Conduction Error

This is performed by using different thermowells of varying insertion length while measuring the temperature of the rotary bath under steady state flow. As per Eq. (5), it is clear that increasing the insertion length (L) allows the sensor temperature (T_i) read closer to the static temperature of the fluid (T_{sg}) [5]. Experiments proved that when the well is fully immersed in the bath, the difference between true value and measured value is as small as $0.09\text{ }^{\circ}\text{C}$ as shown in the Table (1) given below. This loss can be accounted for improper insulation and varying environmental conditions.

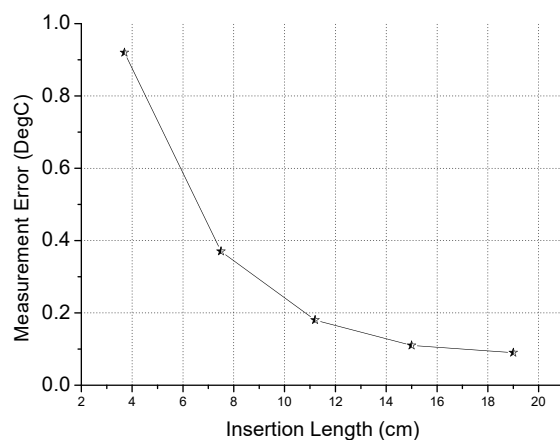


Figure 9. Effect of Conduction Error with variation in Insertion Length of Thermowell

Here, the conduction error can be minimized to only 17.0% by varying the insertion length of the thermowell.

7.0 Conclusions

In the measurement of temperature, it is important that the instrument best suited to the particular problem be selected. The choice will be governed by desired accuracy, accessibility to the material, types of available equipment and economic factors. The requirement for a thermowell should always be considered carefully if accurate measurement is required. The natural frequency of the thermowell must be well above the forcing frequency induced by vortex shedding – so the higher the line velocity, the shorter and thicker the well should be. Similarly, bending stress requirements call for shorter, thicker thermowells as fluid forces increase. On the other hand, shorter thermowells also increase static errors, and thicker thermowells increase dynamic errors. Based on the case study carried out on custom designed thermowell over ASME PTC 19.3 guided designs, it has been confirmed that the performance parameters along with optimization of response time and strength aspect has improved under similar boundary conditions. Hence, regardless of all the errors and process extremities, proper design of thermowell establishes a systematic basis for imparting mechanical stability as well measurement accuracy.

Nomenclature

- L = insertion length, inch
- E = modulus of elasticity of well material at use temperature, psi.
- γ = specific wt. of the material at use temperature, lb per cu in.
- A_s = root Sectional area of the thermowell.
- D_2 = Outer tip diameter of thermowell (inch)
- D = Bore diameter of thermowell (inch)
- w = specific gravity (lb/ft^3)
- λ = Frequency Coefficient
- V = fluid velocity (fps)
- D_A = tip diameter of the thermowell (inch)
- T_{sg} = static temperature of the fluid (deg F)
- T_i = temperature indicated by the temperature sensor (deg F)
- T_w = temperature at the point of attachment (pipe wall), deg F
- L = insertion length, ft
- $m = (hp/ka)^{1/2}$
- h = convective co-efficient of heat transfer, Btu/hr ft^2 deg F
- p = perimeter of thermowell, ft

k = thermal conductivity of temperature sensor,
Btu/hr/ft deg F
a = conduction cross section area of the
thermowell, ft²
 ΔP_{Max} = maximum pressure drop

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- 2) Development of computer code (TEWEL) for various types of thermowell design using Visual Basic.
- 3) C&I, flow element design for AHWR Thermal Hydraulic Test Facility (ATTF).
- 4) Design and development of bidirectional venturimeter for flow measurement in case of flow reversal under accidental scenarios.
- 5) Effect of heat transfer and its analysis on temperature measurement due to insertion of thermowell assembly.
- 6) Methodology development to investigate the performance degradation of surface mounted RTD sensors in operating plants.
- 7) Design and development of integral orifice and orifice plates for ATTF facility, FMTF facility at Tarapur.

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