THERMOPHYSICAL MEASUREMENTS

METHODS AND MEANS FOR CALIBRATING SURFACE TEMPERATURE TRANSDUCERS

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The errors of contacting transducers which are used for measuring surface temperatures of industrial objects and are cited in literature [1-5] are not altogether trustworthy, since either the technique of their calibration is not described at all, or they are calibrated under conditions which differ completely from those of their industrial utilization.

If a thermosensitive element is calibrated separately according to the thermocouple immersion technique, then the temperature transducer which has such an ideally calibrated element and is placed on the tested surface will measure temperature under actual industrial conditions with a systematic error which (depending on the upper temperature measuring limit) will be 5-10 times higher than the tolerated error specified for thermocouples by the All-Union State Standard (GOST) 3044-61. This error is due to many factors, including the specific (total) contact area of the thermal transducer with the measured surface (and the surface finish of both), the heat conduction and thickness of the thermal transducer walls, and the thermal insulation of the thermosensitive element from the surrounding air. A source of errors which cannot be controlled consists of the heat removal along the fixing of the thermal element of the surface transducer's casing components or accessories whose temperatures are always below that of the measured surface.

Thus, surface temperature transducers cannot be provided a priori with any rules or formulas for finding this error analytically. It is only by calibration or testing of the transducer under conditions which simulate the actual industrial application conditions that it becomes possible to evaluate its total error. However, for this purpose uniform requirements and a corresponding technique must be provided.

The organizations which develop or test surface temperature transducers have at their disposal vapor thermostats [6]. However, in addition to their advantages (reproducibility and adequate stability of reference temperatures) the reference thermostats have also certain deficiencies which in many instances prohibit their application.

As a matter of fact, according to the procedure instructions [6], the temperature of the reference surface (the thermostat lid) onto which the tested thermal transducer is placed is assumed to equal the boiling point temperature of the thermostat's heat-transfer agent (water, naphthalin, or sulfur). However, neither the careful measurement of the vapor temperature with the atmospheric pressure taken into consideration, nor the stringent surface finish requirements of the lid can eliminate the systematic error which is then incurred.

As a result of the radiation and convection heat exchange with the surrounding air, the temperature of the vapor-thermostat lid surface will always be in a steady heat-exchange state lower than that of the vapor. A qualitative expression for the difference between the internal and external (reference) thermostat lid temperatures can be easily obtained analytically. By equating the quantity of heat which, in a stable heat-exchange condition, passes per unit time through the thermostat lid (the Fourier heat-transfer law for a plane wall [7]) to the same quantity of heat which this lid loses to the surrounding air (Newton's law of convection heat exchange [7]), we obtain:

\[
\tau_{S}(x) = \tau_{S}(0) + \frac{\tau_{S}(0) - \theta}{\lambda} x,
\]

where \(\tau_{S}(0)\) is the temperature of the reference surface, \(\tau_{S}(x)\) is the temperature of the internal surface of the lid, \(x\) is the thickness of the lid, \(\lambda\) is the heat-emission coefficient of the lid, \(\theta\) is the ambient temperature, \(\alpha\) is the total heat-emission coefficient (\(\alpha = \alpha_{\text{conv}} + \alpha_{\text{rad}}\)).


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TABLE 1. Measurement Results of the Total Inherent Error of Reference Vapor Thermostats at Ambient Air Temperatures of 22-23°C

<table>
<thead>
<tr>
<th>Type of reference thermostat</th>
<th>Boiling temperature, °C</th>
<th>Type of transducer</th>
<th>Temperature transducer readings, °C</th>
<th>Error, °C</th>
<th>Place of measurement (radius), mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>98.9</td>
<td>Stationary</td>
<td>96.5</td>
<td>-2.4</td>
<td>30</td>
</tr>
<tr>
<td>ditto</td>
<td>98.9</td>
<td>Portable</td>
<td>92.8</td>
<td>-6.1</td>
<td>0</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>216.3</td>
<td>Stationary</td>
<td>206.9</td>
<td>-9.4</td>
<td>30</td>
</tr>
<tr>
<td>ditto</td>
<td>216.3</td>
<td>Portable</td>
<td>202.7</td>
<td>-13.6</td>
<td>0</td>
</tr>
<tr>
<td>ditto</td>
<td>216.3</td>
<td>Portable</td>
<td>203.7</td>
<td>-12.6</td>
<td>30</td>
</tr>
</tbody>
</table>

Therefore, the temperature of the reference surface is always lower than that of the internal surface of the lid. For a water thermostat this inherent systematic error is insignificant. However, it will be seen from (1) that with a rising temperature of the reference surface this error will increase and become very substantial for a naphthalene, and especially for a sulfur thermostat. Moreover, the increasing temperature of the reference surface of the lid (in our case a copper one) produces an almost linear rise in the total heat-emission coefficient $\alpha$ [8], whereas the heat-conduction coefficient $\lambda$, on the contrary, decreases, thus also producing according to (1) a rise in the difference between $t_s(x)$ and $t_s(0)$, owing to both the first and second arguments.

A second corollary can be derived from (1):

$$
\dot{t}_s(x) = \dot{t}_s(0) + \frac{\alpha}{\lambda} \left( t_s(0) - t_s(x) \right),
$$

i.e., by reducing to the minimum the thickness of the lid it becomes possible to obtain a reference surface temperature which approaches that of the internal surface of the lid. However, a reduction in the thickness of the lid decreases its strength, thus leading to intolerable plastic deformations in attempting to establish the required thermal contact between the tested transducer and the reference surface which is made unsuitable for repeated measurement. Moreover, at the place where the industrial surface temperature transducer is located the steady heat-exchange condition is disrupted and a local distortion of the reference surface temperature field is produced. Depending on the design and thermal capacity of the transducer, the error in estimating its temperature under these conditions often exceeds the tolerated value [6].

Expression (1) does not take into account the thermal resistance of the water layer which is formed by the condensation of vapor on the internal surface of the thermostat lid (film condensation). Since the water layer has a heat conduction which is hundreds of times smaller than that of the lid, it produces an additional temperature drop. This drop is insignificant in a water thermostat, whereas the low heat conduction of naphthalene, and especially of sulfur, raise in their respective thermostats the difference between the temperatures of vapor and the reference surface.

It should be noted that the design and principle of operation of thermostats are such that the vapor pressure of heat-transfer agents (water, naphthalene, or sulfur) is in a state of equilibrium with atmospheric pressure. In other words, the vapor of heat-transfer agents is mixed with air, and this reduces considerably the heat transfer from vapors in condensation, since it is only the vapor that condenses on the cold walls, whereas air is not affected. In the absence of convection the air eventually accumulates near the walls, thus producing a considerable resistance to the movement of vapor. The heat-emission factor of a heat-transfer agent’s vapor is reduced to 60%, if the vapor contains only 1% of air [9]. In commercial condensers the air is constantly drawn off. This is not done, however, in the above-mentioned thermostats.