be clean. The boilers supplying steam should be so operated that there will be no carryover of solids during the tests and the piping should be thoroughly blown down before assembly of the flow nozzles in it. A means of access should be installed immediately following the flow nozzle so that it can be inspected and cleaned, if necessary, without removing it from the pipe.

4. Long-radius, low-ratio flow nozzles made of 12–14 per cent chrome-iron appear to be dimensionally stable at temperatures up to at least 940°F. In our experience, also, flow nozzles of this material have not shown any corrosive attack when used for steam or condensate.

5. The orifices in the steam-flow line to the turbine checked flow measurements by the three other means very well as indicated by the data in Table 14.

Table 14 Test ratios

<table>
<thead>
<tr>
<th>Method</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Nozzle</td>
<td>1.009</td>
<td>0.994</td>
<td>0.990</td>
</tr>
<tr>
<td>(b) Heat balance</td>
<td>1.007</td>
<td>0.999</td>
<td>1.003</td>
</tr>
<tr>
<td>(c) Exhaust orifice</td>
<td>1.008</td>
<td>1.001</td>
<td>1.004</td>
</tr>
</tbody>
</table>

If only uncalibrated orifices had been available for this turbine test the average of all flows would have been accurate to 0.1 per cent and no flow would have been more than 0.9 per cent in error. Although excellent agreement of orifice-metering methods is shown by the foregoing data, until weighed condensate calibrations can be made, precise statements regarding the accuracy of orifice-metering at elevated steam temperatures and pressures cannot be made. No single set of experiments no matter how carefully conducted can advance the art of steam-flow measurement at these conditions, and the need is clear for more work in this range, particularly for weighed-condensate calibrations.

Acknowledgments

Work of this nature is the result of the efforts of many persons, the authors being those privileged to present it. The personnel of the General Electric Company, Medium Steam Turbine, Generator and Gear Department, Lynn, Mass., and the U. S. Naval Boiler and Turbine Laboratory, Philadelphia, Pa., are responsible for the actual conduct of this work and their efforts are gratefully acknowledged.

Bibliography


APPENDIX

General Equations for Flow Coefficients of Square-Edged Orifices for Use With 1-D and 1/2-D (Radius) Taps as Furnished by Howard S. Bean.

The tables to be included in the fifth edition of the ASME Fluid Meters Report have been computed from these equations. All calculated flow coefficients for the square-edged orifices used in this paper have been computed from these equations:

Nomenclature

$K$ (number) = flow coefficient (includes velocity-of-approach factor)

$K_0$ (number) = limiting value of $K$ as $Re = \infty$

$D$ (inches) = limiting value of $D$ as $Re = \infty$

$\beta$ (ratio) = ratio of orifice diameter to pipe diameter

$R_D$ (ratio) = Reynolds number based on pipe diameter

$\lambda$ (ratio) = 1000/$\sqrt{R_D}$

$b$ (number) = slope of $K - \lambda$-lines

Equations

\[
K = K_0 + b\lambda \quad \text{[1]}
\]

\[
K_0 = (0.6014 - 0.01352D^{-1/4}) + (0.3760 + 0.07257D^{-1/4})
\]

\[
0.00025 \left( \frac{D^4\beta^2 + 0.0025D}{D^2} + \beta^4 \right) \quad \text{[2]}
\]

\[
b = \left( 0.0002 + \frac{0.0011}{D} \right) + \left( 0.0038 + \frac{0.0004}{D} \right)
\]

\[
[\beta^2 + (16.5 + 5D)\beta^4] \quad \text{[3]}
\]

Discussion

K. C. Cotton. The authors have done a commendable job of pointing out some of the difficulties encountered in measuring steam flow. I certainly agree that it is necessary to use a calibrated precision flow-measuring device when striving for accuracies of the order of magnitude of ±0.2 per cent. A device of this type should be installed just prior to the test to avoid the possibility of deposits or damage and removed immediately after the test for inspection.

In testing large steam turbine-generator units the problem of obtaining an accurate measurement of steam flow becomes extremely difficult for the following reasons:

1. Lack of facilities capable of accurately calibrating at the proper temperature, pressure, and flow.

2. Problems involved in the installation of a removable flow section in high-pressure and temperature lines.

3. Thermodynamic loss associated with properly designed flow-measuring devices.

Our experience shows that the performance of large steam turbines can be accurately determined by calculating steam flow based on measured condensate flow, heat balances around feed-water heaters, and the measurement of extraneous steam and water flows. This method is discussed by E. M. Kratz in ASME Paper No. 54-A-25, entitled "Experience in Testing Turbine-Generators in Central Stations." Mr. Kratz also compares the results with those obtained from station stream flow measurements. However, this method requires considerable instrumentation and careful isolation of the cycle during the test. It would simplify our problems if an accurate measurement of steam flow could be made; therefore, I agree with the authors that there is a need for more experimentation and knowledge of steam-flow measurement at elevated temperatures and pressures.

There is also a need for facilities capable of calibrating water flow measurements at the proper Reynolds number for large steam turbine-generator tests.

Authors’ Closure

We thank Mr. Cotton for his discussion and agree with his conclusions.

We are particularly interested in his comment on the lack of

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facilities for calibrating flowmetering devices at proper temperature, pressure, and flow rate. Several laboratories are equipped to calibrate very large condensate flows at room temperature. However, working temperatures at normal test flow measuring points may run as high as 300 F in modern regenerative feed heating cycles. At this temperature the Reynolds number for a given metering element at a given pressure drop is five times that at 70 F. The writers know of no facility that is available for calibration of flowmetering elements with condensate at temperatures in the usual flow measurement range.

It is customary to assume that coefficients of discharge for flow nozzles and flow coefficients for orifices can be extrapolated with good accuracy to high Reynolds numbers from data at lower Reynolds numbers, provided the calibration data are extended to regions where the curves tend to flatten off. However, we cannot evaluate test data with precision unless calibrations at the test conditions have been made. Our tests with steam show that long extrapolations may not be justified if the desired accuracy is to be maintained, but we do not have enough data to draw any firm conclusions.

The Fluid Meters Committee of the ASME is aware of these problems and has instituted a long-range program of investigation. A special subcommittee has been formed to undertake a research program in the problems of high-pressure high-temperature steam and water-flow measurement. It is hoped that industry will provide the necessary support to make the needed facilities available.