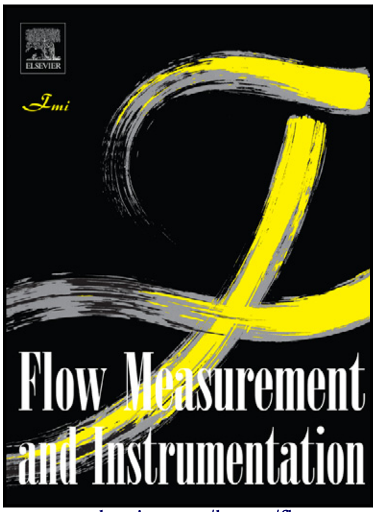


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# Analytical solutions using the thermodynamic efficiency method for absolute flow measurement

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**Abstract**

Manufacturers of large-scale hydraulic machines face high liquidated damages if they cannot meet performance guarantees. Accurate determination of efficiency, power and flow is therefore of great interest. For plants exceeding heads of 100 m, the thermodynamic method is the standard approach. We present a mathematical refinement that uses additional power measurements to achieve an analytical solution for the flow. Under excellent thermal conditions, the measurement uncertainty is lower than that associated with other methods of absolute flow measurement at medium heads. For higher heads an even lower uncertainty can be expected.

*Keywords:* water, thermodynamic method, efficiency, flow measurement, turbine, pump



## 1. Introduction

The thermodynamic method is the principal approach to determining the efficiency of hydraulic machines. It makes use of the first law of thermodynamics, which implies energy conservation. Any mechanical and fluid friction causes energy conversion of hydraulic energy into thermal energy. Thus, hydraulic losses can be determined by means of accurate water temperature measurements upstream and downstream of the hydraulic machine. Water is heated by approximately $|\theta_2 - \theta_1| = 2.4$ mK per 100 m of head and per 1% loss of hydraulic efficiency.[1] The lower the available head, the larger the geometric dimensions of the hydraulic parts and the more thermometers[2] are necessary to obtain reliable values for the thermal distribution. Hence, this method is limited to machines operating with net heads of more than 100 m [1].

Poirson and Babbillion first demonstrated the applicability of the thermodynamic efficiency method in 1920 [2]. They were able to determine the hydraulic efficiency $\eta_h$ with lower uncertainty than the standard method at the time. More than 30 years passed before necessary progress in theory and experiment was made by the engineers Willm and Campmas in 1954 [3]. They set the instrumentational standard of thermally insulated extraction probes for external temperature measurement, which is still in use. At that time, practitioners concluded that omitting the dynamic energy term – which describes the difference in kinetic energy between high-pressure and low-pressure sections – does not substantially change the efficiency value, since the dynamic term amounts to only a few percent of the pressure term [4]. It seemed to be sufficient to determine the discharge $Q$ by means of any technique or device, even with high uncertainty. In the 1950s and 1960s the discharge was therefore determined either by measuring the dynamic pressure [5, 6] or by estimating its value [7, 8].

Nowadays, manufacturers of large-scale hydraulic turbines and pumps face high liquidated damages if their efficiencies fall below the performance guarantees by even 0.01%, making the need for high-accuracy discharge evaluation evident. Interestingly, Willm and Campmas already mentioned the possibility of calculating the discharge with the thermodynamic method in their publication from 1954.[3] It only requires determining the mechanical power $P_m$ by means

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[1]We obtain the indicated value by simplifying the specific mechanical energy to $E_m \approx E - c_p(\theta_2 - \theta_1)$ and rearranging equation (1), neglecting any heat exchange term.

[2]The systematic uncertainty level of the high-precision thermometers is in the order of ±1 mK.

[3]They presented a special case in using extraction probes in both pressure sections.