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A selected literature review of efficiency improvements in hydraulic turbines

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ABSTRACT

Knowing the efficiency of a hydraulic turbine has important operational and financial benefits to those who operate a plant. Historical efficiency and other data on turbine performance are essential for the informed selection and use of turbines. So having such a database from different manufactures is attractive. However, at present it is almost impossible to get a universal database to reflect the turbine characteristics. This paper reviewed a set of empirical equations to replacefull database which defines the peak efficiency and shape of the efficiency curve as a function of the commissioning date for the unit, rated head, rated flow and other main design parameters. Since the design theories, methods and tools of turbines are relatively mature, and the majority of turbine manufacturers have reached a level of know how which enables them to carry out hydraulically and structurally correct units to product high-performance turbines. This paper paid more attention to the design factors, which could influence the value of the practically attainable overall turbine efficiency. To quantify the effects of these factors, this paper investigated the influence of roughness and gap clearances on the internal leakage flow rate. Testing and CFD are the most two important tools in different design stages. This paper reviewed some key ideas and issues on the efficiency research in both. At last, improvement measures based on these above mentioned design factors were provided.

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1. Introduction

Hydropower has been a proven, extremely flexible, and well-advanced technology for more than one century. At present, its technology is very mature. Still, there is some room for further improvements. Turbine efficiency is likely the most important factor in a unit. As the heart of the system, design of a turbine is focused on this to obtain the maximum efficiency. The maximum efficiency can be reached when all losses are kept to a minimum.

In general, peak efficiencies of Francis turbines with modern design tools like CFD method have enabled to achieve the range of 93% to almost 96%. The position that peak efficiency occurs varies between 80% and 95% flow. For Kaplan turbine, the position that peak efficiency occurs varies between 94% and 100% flow. Efficiency loss at higher heads drops 2 to 5 percent points below peak efficiency at the design head, and as much as 15 percent points at lower heads. For multi-nozzles Pelton turbines, the high efficiency zones are even broader due to the number of operating jets can be varied. The position that peak efficiency occurs varies between 65% and 80% flow. Crossflow turbines are only used in the lower power range. Generally, large turbine refers to single unit with a capacity of more than 50,000 kW, and small turbine refers to unit capacity of 100 kW to 50,000 kW. Turbines can reach high efficiency under normal circumstances, but rather low efficiency during small flow rate. With total efficiencies from 84% to 87% [1], the peak efficiency is a little less than that of other turbines.

2. Mathematical model for predicting turbine efficiency

It is difficult to find out on turbine efficiency data in detail in most paper, while manufacturers are reluctant to divulge data. Since manufacturers regard such information as proprietary that could compromise a competitive advantage. So in some cases it is challenging and not flexible to obtain the turbine efficiency due to time, budgetary, or other constraints. J.L Gordon [2] did a very good job to develop a set of empirical equations for calculation of turbine runner efficiencies, taking the increase in efficiency of newer designs and deterioration since commissioning into account. The method outlined by Gordon is a generic procedure, with calibration factors for different turbines. The accuracy of Gordon's method is within $\pm 3\%$. These equations are intended as an aid in

- Estimating new runner performance at the feasibility study stage and
- Estimating old runner performance where it is impractical to undertake efficiency tests or where commissioning test records are unavailable.

At last, these equations with their plotting curves are very useful to help understand the development of the efficiency level of turbines, and different efficiency characteristics of different types of turbines.

For reaction runners, the peak efficiency equation has the following form:

$$\varepsilon_{peak} = A - \Delta\varepsilon_{year} - \Delta\varepsilon_{specificspeed} + \Delta\varepsilon_{size} \quad (1)$$

where A is a constant value depending on the type of the runner; $\Delta\varepsilon_{year}$ is the efficiency change due to the year the unit was commissioned; $\Delta\varepsilon_{specificspeed}$ is the efficiency change due to specific speed; and $\Delta\varepsilon_{size}$ is the efficiency change due to size.

This equation indicates that four parts influence the peak efficiency. The first one fixed the base level of the peak efficiency. Based on the statistics of a large sample of data in a lot of operating hydropower plants, A has a value of 0.9187 for a Francis runner and 0.904 for Kaplan and axial flow runners. The difference in the base level is 1.47%, double the 0.75 difference given in ASME data [3]. The second one shows the difference in ages and commissioning. The first three parts determine the peak model efficiency. And the last one is a modification on the prototype size and the runner throat diameter. For the details of exact peak efficiency and shape equations and scope of them could see Gordon's paper [2].

Manness and Doering [4] developed Gordon's method, with a large Manitoba Hydro's data. Furthermore, Manness's method includes the effects of rerunnering turbines in his model while Gordon's does not. The accuracy of refined model is within $\pm 2\%$ for an older turbine, and within $\pm 1\%$ for new one.

3. Design factor affecting turbines efficiency

3.1. Introduction

The majority of the hydraulic turbine manufacturers have reached a very high level of knowhow which enables them to carry out hydraulically and structurally correct designed turbines. So the value of the practically attainable overall turbine efficiency η is mainly influenced by factors such as surface roughness of parts that are in contact with the flow, and the internal leakage flows through the gaps between the blades and shroud. The former means the performance of a turbine can degrade over time, due to erosion damage, cavitation damage and weld repairs, etc. The latter also could get worse due to erosion wear.

Fig. 1 shows a breakdown of the loss distribution within a Francis turbine as a function of specific speed [5]. The value of specific speed directly corresponds to the shape of the runner. With lower specific speeds, the volumetric losses as well as losses due to runner disk friction are very significant. For high head Francis turbines, the efficiency due to disk friction can reach up 1.0% [6]. For higher specific speeds, the influence of blade friction losses and exit swirl losses in draft tube dominates and mainly determines the level of the overall efficiency. There are similar results for other types of turbines [3]: turbine efficiency is a function of the specific speed, with both low and high specific speed turbines having lower peak efficiencies than medium ones. At lower heads, losses in the draft tube are increasingly significant; at high heads, flow losses through the runner seals increase. Lastly,