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A power loss model for Archimedes screw generators

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ABSTRACT

This paper presents a complete power loss model for an Archimedes screw used for power generation (ASG) including a non-dimensional model to predict power losses due to outlet submersion flooding. This model amends a prior idealized, frictionless ASG performance model to include power losses due to bearing friction, outlet exit effects, internal hydraulic friction and outlet submersion. This study presents data and a derived relationship for power losses due to outlet submergence and found that unmodified Manning's coefficients can be used to model internal fluid friction losses. Laboratory experiments on a scale-model ASG were conducted to determine variable relationships and validate power loss models. The performance of a 7 kW grid-connected ASG was measured and used to validate model predictions. The proposed ASG power loss model improves the prior frictionless power model significantly and was generally capable of predicting the power output of a real-world ASG.

1. Introduction

Archimedes screw generators (ASGs) are an emerging form of microhydro electric power generation. This is a recent application of the Archimedes screw, an ancient device long used for water pumping [1]. The vast majority of ASGs have been installed in Europe. Since 1993, more than 400 ASGs have become operational in Europe [2]; in North America, there is currently one grid-connected ASG unit in Waterford, Ontario, Canada installed by Greenbug Energy Inc. [3].

The central component of an ASG is the Archimedes screw. An Archimedes screw is a set of interlaced helicoid planes, termed flights, fixed to a central cylindrical shaft. The screw is contained in an enclosing trough. Typically, a small gap exists between the trough and screw, allowing the screw to rotate freely within the fixed trough, but occasionally the trough is connected directly to the screw flights and rotates with them. Water introduced to the top (inlet) of an inclined, rotating ASG transverses the screw from high to low elevation and exits at the bottom of the screw (outlet). Water moving down the axial length of the screw is entrapped between two adjacent screw flights, forming discrete volumetric units, termed buckets. The inclined orientation of the individual buckets with respect to the screw axis produces differences in water depths on either sides of the screw flights, resulting in a net pressure difference across the flights. The helicoid shape of the flights causes a component of this pressure force to act tangentially to the central screw axis, creating a torque that causes mechanical rotation of the screw. If a generator is attached to the screw, this mechanical rotation can be used to generate electricity.

According to Williamson et al. [4], ASGs are best suited for low-head and low-flow sites. Comparing several microhydro turbines relative to design selection criteria for specific sites, ASGs were found to perform advantageously over traditional turbines for sites with head less than 5 m because they remain highly efficient even as available head approaches zero [4]. Dellinger et al. [5] suggest ASGs perform best at sites with less than 10 m of head and 10 $m^3 s^{-1}$ of flow.

ASGs have proven to be an efficient technology. Lyons [6] found mechanical efficiencies in small (2 W) laboratory scale ASGs greater than 70% and a 400 W prototype ASG was found to have a peak electricity generating efficiency of 74%. Real-world ASGs show similar efficiencies. Analysis of commercial ASGs in Europe found a mean operational efficiency of 69% and maximum efficiency of 75% [7]. ASGs operating in Germany have efficiencies of approximately 80% [8].

ASGs are an attractive technology because of the limited impacts incurred on wildlife and aquatic species. Unlike traditional turbines, ASGs operate at low rotational speeds and have large openings that allow aquatic species to pass through safely with a minimum of morbidity or mortality. Kibel et al. [9] demonstrated that fish with masses smaller than 1 kg can safely pass through an

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ASG rotating at typical operating speeds. Utilizing rubber bumpers on the leading edges of ASG flights can ensure that fish up to 4 kg can safely pass through ASGs and species of varying type, including trout, eels, and salmonids, usually pass unharmed through commercial ASG units in the United Kingdom [10].

There are several notable publications on Archimedes screws used as pumps (e.g. Refs. [1,11,12]). Historically, there have been many attempts throughout history to analyze the geometry of the Archimedes screw itself, including by Cardano, Galilei, Bernoulli, Hachette and Weisbach, however, due to the difficulty in finding analytical solutions to the screw geometry, all historical attempts to quantify the geometry were either limited or empirically-based [1]. Rorres [11] derived analytical and numerical relationships for the water levels, flow rates, and flow leakages based on actual Archimedes screw geometry. While Rorres' analysis was intended for Archimedes screw pumps, the resulting relationships are also typically applied to ASGs.

Research specifically on screws used as turbines has been steadily emerging in more recent years. Nuernbergk and Rorres [13] extended Rorres' analysis [11] to determine the inflow head requirements for a steady-state ASG. Gap leakage, or leakage that occurs between the flights and the trough, is accounted for in these models using a physics-based, hydrostatic pressure model. Overflow leakage, or leakage that occurs when water levels permit flow over the top of the central shaft from one bucket to a lower bucket, is accounted for using a weir-type flow model. Nuernbergk's book [14] is the most complete treatment on ASGs to date, and presents a more complete power model including the complete three-dimensional geometry described by Rorres [11] and power losses from gap and overflow leakage as well as previously neglected hydraulic friction. However, this model assumes steady-state conditions, operating under optimal bucket formation (e.g. static water fill levels within the buckets). Furthermore, this model is presented in German, making it difficult to be used as a design tool in North America. Rohmer et al. [15] developed models for ASG performance grounded in the work of Neurnbergk and Rorres, and found good agreement between model predictions and the measured performance of a 0.84 m diameter laboratory Archimedes screw. They noted that one improvement needed was a method of determining friction loss coefficients based on screw properties without using experimental data.

Lubitz et al. [3] derived a power model with variable fill levels within the buckets. The Lubitz et al. model includes the overflow leakage model used by Rorres [11], and utilizes a gap leakage model that is functionally similar but cast in a slightly different geometry. However, the Lubitz et al. [3] model neglects many major power losses such as hydraulic friction, bearing friction losses and losses due to outlet submersion. Therefore, while this varying fill height model allows for power predictions across a larger range of operating conditions, the exclusion of power losses creates limitations of when used as a design tool. This model will be referred to as the Ideal model and is discussed further in Section 2. The Ideal model was compared to experimental measurements and was found to over-predict ASG power as a result of these neglected power losses [3].

A model presented by Dellinger et al. [5] combined and improved upon the geometry and leakage models presented by Nuernbergk [14] and the variable fill levels presented by Lubitz et al. [3] to create the most complete ASG power model to date. This complete model was validated against experimental data collected on a laboratory-scale ASG and satisfactory agreement was found. Dellinger et al. [5] also investigated the effects of previously ignored power losses due to outlet submersion and compared experimental efficiencies to predictions made by Nuernbergk [14] based on optimal geometric considerations. While outlet submersion effects were analyzed, Dellinger et al. [5] did not propose a comprehensive outlet power loss model.

This paper extends the ASG power model ideas offered by Nuernbergk [14], Lubitz et al. [3] and Dellinger et al. [5] to create a complete ASG power model that includes all major power losses. It accounts for leakage and hydraulic friction and also includes a non-dimensional outlet submersion power loss model. Specifically, this work amends the Ideal ASG power model of Lubitz et al. [3] to include all dominant power losses. Additionally, this complete ASG power model is derived from data collected from a laboratory-scale ASG. The data collected from the laboratory-scale ASG is comprehensive, covering a wide range of flow, inlet and outlet basin depths, and rotational speed conditions. Finally, the complete power model presented in this paper is validated against a real-world commercial ASG.

2. Ideal ASG power model

The power losses outlined in this paper are amendments to the Ideal Archimedes screw power model [3]: the same geometric and parameter framework is used. A performance model will be developed based on examining a single ideal bucket within an ASG operating under steady-state conditions (steady flow Q, constant angular rotation speed ω). The shape and size of a bucket is determined entirely by the geometry of the screw (Fig. 1), and is defined by the inner diameter (D_i), outer diameter (D_o), screw pitch (S) (distance along the screw axis for one complete helical plane turn), number of helical plane flights (N), inclination angle of the screw (β), and non-dimensional water fill height of the bucket (f). The flighted length of the screw (L) then fixes the number of buckets (B) along the screw.

The Ideal performance model is actually a collection of individual component models that calculate a wide range of ASG performance parameters based on an ASG's geometry, steady-state rotational speed, and bucket fill level [3]. An infinitely long screw is assumed where all buckets within the screw effectively function identically to the idealized bucket. Positions on the helical plane surfaces are described in cylindrical coordinates, with a screw longitudinal axis 'w' positioned down the center of the screw. Vertical water depths are determined by projecting physical locations on the helical plane surfaces to a vertically oriented Cartesian axis 'z' at an angle of β to the 'w' axis (Fig. 2).

For any given position along the 'w' axis, the radial and angular positions on the leading plane are described by the geometry of a helicoid of pitch length S:

$$r(w) = r \tag{1}$$

and

$$\theta(w) = 2\pi\left(\frac{w}{s}\right) \tag{2}$$

For a single bucket, θ ranges from 0 to 2π and r ranges from $D_i/2$ to $D_o/2$. At any point (r, θ), the vertical position z_1 on the leading (downstream) helical plane surface is then defined by:

$$z_1 = r\cos(\theta)\cos(\beta) - \frac{S\theta}{2\pi}\sin(\beta) \tag{3}$$

The same point on the preceeding (upstream) helical plane, z_2, is defined by:

$$z_2 = r\cos(\theta)\cos(\beta) - \left(\frac{S\theta}{2\pi} - \frac{S}{N}\right)\sin(\beta) \tag{4}$$

Using these point definitions, the minimum and maximum fill