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Penetration depth of plunging liquid jets – A data driven modelling approach

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ABSTRACT

In the case of impinging water jets or droplets, air entrainment processes are crucial to the casing design of hydraulic impulse turbines in the micro-hydro sector. To initiate first steps towards a precise prediction of the complex, multi-phase casing flow of impulse turbines, single aspects such as the penetration depth of impinging liquid jets have to be separated and fully understood. Existing investigations determining penetration depths are related to a very small range of flow rates and therefore show an underestimation of the penetration depth being applied to the casing flow of impulse turbines, which are generally operated at higher flow rates. For a more general description of the air entrainment process, investigations of plunging water jets within an extended flow rate range are conducted and the penetration depth is modelled using a data driven artificial neural network (ANN) approach and a non-linear regression model.

At low flow rates, experiments results are in accordance with existing studies, whereas penetration depths up to 170 cm are measured at higher flow rates. For the mathematical models to achieve a wide range applicability, a large data base is used, including published and measured data. The modelled penetration depths can be precisely verified by the performed measurements and show correct physical behaviour, even in areas without underlying data. Calculation rules, weight matrices and biases of the trained ANN are published to achieve high transparency and scientific improvement in neural modelling of penetration depths of impinging liquid jets.

1. Introduction

The entrainment of air caused by impinging water jets and droplets has a great impact on many technical aspects of hydraulic engineering. For example, in the field of hydraulic machinery, specifically micro-hydro impulse turbines, air entrainment and detrainment processes have a negative impact on the durability of the pipe system and on the overall efficiency of the machinery itself. Investigations on a micro-hydro impulse turbine show that penetration depth is a key parameter for the design of the turbine casing preventing air detrainment. Based on these findings, equations for an optimized casing design of micro-hydro impulse turbines are derived from Kramer et al. [1].

Measurements at large hydropower plant "Koralpe" (Austria) demonstrated that an existing equation derived from Hager [2] seems to underestimate the penetration depth in prototype plants. During the experiments, penetrating air bubbles were observed over the whole tailwater depth, whereas the calculated results clearly showed lower penetration depths [3]. Possible explanations include the underestimation of scaling effects, which occur by disregarding dynamic similarity conditions while transferring results. When comparing different scales of machines, prototype plants have higher flow rates, implying a greater impulse of the impinging water jet and a lower density of the tailwater flow caused by increased air entrainment. Both facts lead to higher penetration depths in the prototype scale. The lack of scale independent measurement results needs to be compensated by more general descriptions.

With regard to minimizing negative consequences of air entrainment in hydraulic structures and equipment, the governing processes have to be clearly identified and air detrainment has to be prevented using optimized design right from planning stage. Aerated flows in hydraulic engineering are complex and therefore challenging to solve with analytical or numerical methods. Recent numerical based contributions in the field of air entrainment and penetration depth of plunging are given in Refs. [4–6]. However, experimental investigations are essential for validation of

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Nomenclature

$\mathbf{a}^i$	neural output vector [–]
ANN	artificial neural network
$\mathbf{b}^i$	bias vector [–]
d_0	nozzle diameter [m]
d_j	jet diameter at plunge point [m]
f	frequency [Hz]
$\mathbf{f}^i$	transfer function [–]
g	gravitational acceleration [m/s^2]
H_P	penetration depth [m]
i	layer of the neural network [–]
$\dot{I}$	momentum flow at plunge point [kg m/s^2]
K^i	number of neurons [–]
l_0	nozzle length [m]
L	number of input parameters [–]
L_j	jet length [m]
m	mass [kg]
max	maximum
min	minimum
n_M	number of measurements [–]
$\mathbf{p}$	vector of input parameters [–]
$\mathbf{p}^n$	vector of input parameters, normalized [–]
Q_w	water volume flow [m^3/s]
RSD	relative standard deviation [%]
s	standard deviation [m]
u_b	bubble terminal velocity [m/s]
v_0	jet velocity at nozzle [m/s]
v_j	impinging jet velocity [m/s]
$\mathbf{W}^i$	weight matrix [–]
h	water level [m]
$\bar{x}$	average of 4 measurements [m]
α	impact angle [°]
β	half spread angle of the jet [°]

numerical results and current knowledge into aerated flows relies mainly on scaled model investigations under specific flow conditions [7]. A comprehensive survey of experimental and theoretical research on gas entrainment by plunging liquid jets is given by Bin [8], while more recent investigations and insights are presented by Kiger and Duncan [9]. Based on phenomenological observations, three different air entrainment regimes (incipient entrainment, intermittent entrainment and continuous entrainment) with three main aeration mechanisms at the plunge point of impinging water jets (aeration due to surface disturbances, aeration due to boundary layer and free surface aeration into shear layer) are identified by Chirichella et al. [10] and Ervine [11], respectively. Commonly used parameters to characterise the process of air entrainment are the bubble size distribution, void fraction, entrainment rate and penetration depth. To determine those parameters, numerous empirical correlations are given throughout the literature, e.g. in Ref. [8], but due to the different experimental conditions, the data from published studies does not allow any generalized applicability.

To provide more generalized functional dependencies of the penetration depth on a wide range of flow rates and jet lengths, detailed experimental investigations are conducted. To avoid scaling effects, full-scale experiments with an extended flow rate range are essential, especially given the multiphase flow processes. For the purposes of data evaluation and assessment, a data-driven neural network model is developed within this work.

1.1. Penetration depth

The penetration depth (H_P) of a plunging free jet is defined as the distance between the liquid surface and the deepest point reached by air bubbles during the entrainment process, see Fig. 1. At this point, the velocity of the bubble equals zero and the buoyancy force becomes dominant. Throughout the transient air entrainment process, the lower limit of the bubble swarm fluctuates continuously [8]. Therefore this point is defined by a timely weighted average rather than by one fixed value.

To determine penetration depth, mainly empirical approaches based on laboratory experiments are available. Correlations are given in Ref. [12]:

$$H_P = 2.6 \cdot (v_0 \cdot d_0)^{0.7} \quad (1)$$

and in Ref. [8]:

$$H_P = 1.20 \cdot v_j^{0.77} \cdot d_0^{0.625} \cdot L_j^{-0.094} \quad (2)$$

where H_P is the penetration depth, v_0 the jet velocity at the nozzle, d_0 the nozzle diameter, d_j the jet diameter at the plunge point and L_j the jet length. The application of the equations listed above is restricted to vertical water jets, although Eq. (2) applies specifically to low velocity jets with $v_0 < 5$ m/s. The influence of the impact angle α on the penetration depth was investigated in Ref. [13], where the jet velocity at the nozzle was varied at angles of $\alpha = 45°$ and $60°$. The functional dependency of the penetration depth on different input parameters is given as:

$$H_P = 4.84 \cdot v_0^{0.73} \cdot d_0^{0.93} \cdot L_j^{-0.21} \cdot (\sin\alpha)^{0.73} \quad (3)$$

Another correlation including the impact angle as well as the spread angle of the jet is presented by Clanet and Lasheras [14]:

$$H_P = \frac{(1 + tan\beta)\cos\alpha + \tan\beta\sin\alpha}{2\tan\beta}\,\frac{\cos(\alpha-\beta)}{\cos\beta}\,\frac{v_0}{u_b}d_0 \quad (4)$$

In the equations above, H_P is the penetration depth, v_0 the jet velocity at the nozzle, d_0 the nozzle diameter, L_j the jet length, α the impact angle, β the half spread angle of the jet (assumed to $\beta = 12.5°$) and u_b the bubble terminal velocity.

All presented equations are based on experiments with low flow rates of few liters per second, whereas for example the average flow rate of 14 micro-hydro impulse turbines used for energy recovery in Switzerland is $Q_w = 35.4$ l/s [15]. At those signif-

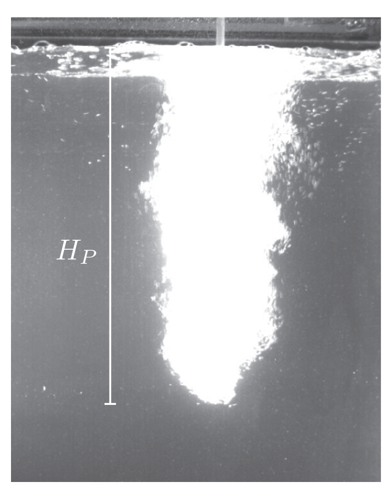

Fig. 1. Penetration depth of a plunging liquid jet.