PRELIMINARY DESIGN OF RDE FEEDWATER PUMP IMPELLER

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ABSTRACT

PRELIMINARY DESIGN OF RDE FEEDWATER PUMP IMPELLER. Nowadays, pumps are being widely used in the thermal power generation including nuclear power plants. Reaktor Daya Eksperimental (RDE) is a proposed nuclear reactor concept for the type of nuclear power plant in Indonesia. This RDE has thermal power 10 MW_{th}, and uses a feedwater pump within its steam cycle. The performance of feedwater pump depends on size and geometry of impeller model, such as the number of blades and the blade angle. The purpose of this study is to perform a preliminary design on an impeller of feedwater pump for RDE and to simulate its performance characteristics. The Fortran code is used as an aid in data calculation in order to rapidly compute the blade shape of feedwater pump impeller, particularly for a RDE case. The calculations analyses is solved by utilizing empirical correlations, which are related to size and geometry of a pump impeller model, while performance characteristics analysis is done based on velocity triangle diagram. The effect of leakage, pass through the impeller due to the required clearances between the feedwater pump impeller and the volute channel, is also considered. Comparison between the feedwater pump of HTR-10 and of RDE shows similarity in the trend line of curve shape. These characteristics curves will be very useful for the values prediction of performance of a RDE feedwater pump. Preliminary design of feedwater pump provides the size and geometry of impeller blade model with 5-blades, inlet angle 14.5 degrees, exit angle 25 degrees, inside diameter 81.3 mm, exit diameter 275.2 mm, thickness 4.7 mm, and height 14.1 mm. In addition, the optimal values of performance characteristics were obtained when flow capacity was 4.8 kg/s, fluid head was 29.1 m, shaft mechanical power was 2.64 kW, and efficiency was 52 % at rotational speed 1750 rpm.

Keywords: Blade, impeller, pump, RDE

ABSTRAK

DESAIN AWAL IMPELER POMPA AIR UMPAN RDE*. Saat ini, pompa digunakan secara luas dalam pembangkit tenaga termal termasuk pembangkit listrik tenaga nuklir. Reaktor Daya Eksperimental (RDE) merupakan konsep reaktor nuklir yang diusulkan untuk tipe PLTN di Indonesia. RDE ini memiliki daya termal 10* MW_{th}*, dan menggunakan pompa air umpan dalam siklus uapnya. Kinerja pompa air umpan bergantung pada ukuran dan geometri model impeller, seperti jumlah sudu dan sudut sudu. Tujuan dari penelitian ini adalah untuk membuat rancangan awal impeller pompa air umpan untuk RDE dan untuk mensimulasikan karakteristik kinerjanya. Kode Fortran digunakan sebagai bantuan dalam penghitungan data untuk untuk mengkalkulasi secara cepat bentuk sudu impeller pompa air umpan, terutama pada kasus RDE. Analisis perhitungan dipecahkan menggunakan korelasi empiris yang terkait dengan ukuran dan geometri model impeller pompa, sedangkan analisis karakteristik kinerja dilakukan berdasarkan diagram segitiga kecepatan. Pengaruh bocoran, melalui impeler akibat celah yang diperlukan antara impeller pompa air umpan dan saluran volute, juga dipertimbangkan. Perbandingan antara pompa air umpan HTR-10 dan RDE menunjukkan kemiripan dalam garis tren bentuk kurva. Kurva karakteristik ini akan sangat berguna untuk perkiraan nilai kinerja pompa air umpan RDE. Desain awal pompa air umpan memberikan ukuran dan geometri model sudu impeller dengan 5-sudu, sudut masuk 14,5 derajat, sudut keluar 25 derajat, diameter dalam 81,3 mm, diameter luar 275,2 mm, ketebalan 4,7 mm, dan tinggi 14,1 mm. Selain itu, nilai optimal karakteristik kinerja diperoleh ketika kapasitas aliran 4,8 kg/s, head fluida 29,1 m, tenaga mekanik poros 2,64 kW, dan efisiensi 52 % pada kecepatan putaran 1750 rpm.*

Kata kunci: Sudu, impeler, pompa, RDE

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INTRODUCTION

The pumps have been widely used for fluid recirculation in thermal power generation including nuclear power plants [1-3]. The pump works by converting mechanical energy into hydraulic energy. Mechanical energy is generated by impeller as a rotating component of the pump. Hydraulic energy is produced by centrifugal force acting on fluid (water). The performance characteristic of a pump is influenced by this impeller. This performance characteristic includes head and efficiency. The impeller comprises a number of rotating blades where blade is one of the most important parameters in design of pump impeller. At the impeller, blockage effect phenomenon is quite serious and the flow velocity increases if the number of blades was too many. The increase of interface between fluid stream and blades will cause the increment of hydraulic losses. Whereas if the number of blades was too few, the diffuser losses will increase the grow of diffuse extent of the flowing passage [4,5]. Other important parameters such as blade angles, blade diameter, eye diameter, flow capacity, and a rated rotational speed of pump shaft must also be considered in the design task of pump impeller [5]. Preliminary design of a feedwater pump model is based on the determination of size and geometry of impeller blade, and shaft power for desirable head.

Reaktor Daya Eksperimental (RDE) has been proposed as the concept of nuclear power plant type in Indonesia [6]. This RDE adopts a pebble bed high temperature gas-cooled design with core thermal power 10 MW_{th}, and employs a feedwater pump within its steam cycle [6]. This paper presents a preliminary design of new impeller for a feedwater pump of RDE. The pump model under consideration is of the centrifugal type in which the impeller rotates within a volute casing. It is well known that full data of a pump performance characteristics is essential for informing the technical specification of pumps. However, it can be difficult to obtain the detailed information required, the data of pumps from different literatures will be referenced [7-10]. In this study, a Fortran computer code is developed to predict performance characteristics of a RDE feedwater pump based on a number of impeller blade, and the calculation results of this numerical simulation will be compared with the existing operation data for a type of feedwater pump of HTR-10, China [11-14]. This computer program is developed by giving only the required design parameters of a pump impeller model for a RDE case. The solution method is by utilizing of empirical correlation which are related to size and geometry of a pump impeller model, and diagram characteristics of velocity triangle.

MATHEMATICAL FORMULATION

The pump impeller geometry is preliminary designed based on the head and mass flow rate as discharge. Figure 1 shows an example of pump impeller [4]. The following are some formulas involved in computing preliminary design of a pump impeller model.

- The specific speed (n_s in dimensionless) can be calculated by the following formula [developed from the reference 15] :

$$n_s = \frac{K_1 \sqrt{Q}}{H^{0.75}} \tag{1}$$

where K_1 is a constant value (= 2852.5), Q (in kg/s) is mass flow rate, and H (in m) is fluid head in the impeller model for the internal passage of feedwater pump.

- The mechanical shaft power, (P_{sh} in kW) required can be calculated by using the following formula [developed from the reference 15] :

$$P_{sh} = \frac{\gamma Q H}{K_2 \eta} \tag{2}$$

where K_2 is unit conversion (= 1.0 x 10^6), γ (in N/m^3) is specific weight of fluid and η (in dimensionless) the feedwater pump efficiency.

- The impeller diameter (d in m) can be found by using the formula [developed from the references 16 and 17] :

$$d = \frac{K_3\, u}{\pi\, n} \tag{3}$$

where K_3 is unit conversion (= 60), u (in m/s) is tangential velocity, π is a constant value (= 3.14), and n (in rpm) is rotational speed of impeller.

Figure 1. An example for geometry of pump impeller [4]

Figure 2 shows inlet and outlet velocity triangles in the present pump impeller. At inlet condition, the fluid moving with an absolute velocity v_1 enters the pump impeller through a cylindrical surface of radius r_1 and angle β_1, as shown in Figure 2. At outlet condition, the fluid leaves the pump impeller through a cylindrical surface of radius r_2, with absolute velocity v_2 inclined to the tangent at the angle β_2, as also shown in Figure 2. From the diagram of velocity triangles on Figure 2, the following relationships are established by using cosine rule :

$$u_1 v_1 \cos\beta_1 = \frac{\left(u_1^2 - v_{1,rel}^2 + v_1^2\right)}{2} \tag{4}$$

$$u_2 v_2 \cos\beta_2 = \frac{\left(u_2^2 - v_{2,rel}^2 + v_2^2\right)}{2} \tag{5}$$

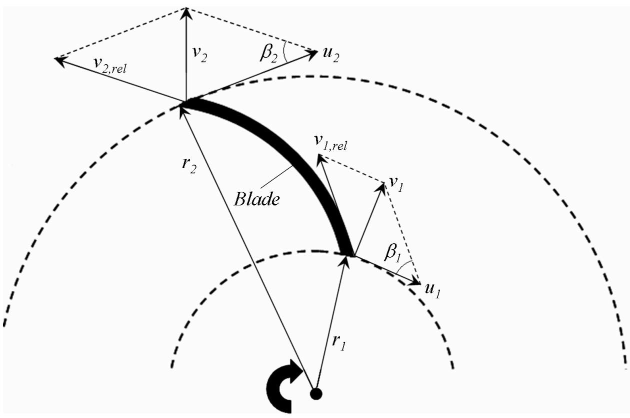

Figure 2. Velocity diagram for new impeller model

Euler fluid head (theoretical head) along with the physical geometry of pump impeller is determined as follows [developed from the Equation (6) on reference 16]:

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$$H_E = \frac{\left(v_2^2 - v_1^2\right) + \left(u_2^2 - u_1^2\right) + \left(v_{1,rel}^2 - v_{2,rel}^2\right)}{2g} \tag{6}$$

where H_E (in m) is Euler fluid head, v_1 (in m/s) is absolute velocity at inlet, v_2 (in m/s) is absolute velocity at outlet, u_1 (in m/s) is tangential velocity at inlet, u_2 (in m/s) is tangential velocity at outlet, $v_{1,rel}$ (in m/s) is relative velocity at inlet, $v_{2,rel}$ (in m/s) is relative velocity at outlet, and g is the acceleration of gravity (= 9.8 m/s^2). In the above Equation (6), the first term (v_2^2-v_1^2) denotes the increase in kinetic energy of fluid flow in impeller model. The second term (u_2^2-u_1^2) represents the energy used in setting the fluid through a circular motion about impeller. The third term ($v_{2,rel}^2$-$v_{1,rel}^2$) is the region of static head due to a reduction in the relative velocity in the fluid flow passing through the pump impeller model.

METHODOLOGY

In this section, the effect of leakage passing through the impeller model due to the required clearances between the feedwater pump impeller and the volute channel is considered. Losses which might be attributed to the friction between fluid and impeller model during fluid passage, and diffuser loss are also considered. Losses due to Reynolds's number effects are neglected. For calculation simulation of the fluid flow within the feedwater pump impeller model, the governing Equations (1) until (6) will be applied for obtaining impeller geometry and pump performance charactristics of a RDE case. The Figure 3 shows the flowchart of calculation steps to solve the feedwater pump impeller model. The yellow box consists of two steps. The first step is to design the size and dimesion geometry with simple linier constraints such as desired discharge pressure, impeller rotational speed, blade angles, and blade shape (as in Fig.2). The discharge pressure is assumed to be able to cope the pressure losses within the pump impeller and the volute. These parameters are considered in the preliminary design of the impeller diameter. The number of blade is given to calculate the total area of blades. Otherwise, the second step updates the Euler fluid head by using Equation (6). The number of impeller blade can be changed from the starting procedure. This procedure continues up to the total iteration of completion is achieved. Table 1 shows specifications data of the preliminary design for a feedwater pump model of a RDE case. Furthermore, the calculation result of this Fortran code is compared with an existing data of feedwater pump within HTR-10 case which have the operation performance, as shown in Table 2. This comparison is intended to know the trend line of the curve shape. Hydraulic losses (H_L) is calculated by considering mass flow rate of internal leakage and mass flow rate at impeller blade. Diffuser losses (D_L in %) is calculated by considering mass flow rate, number of blades, rotational speed, and impeller diameter.

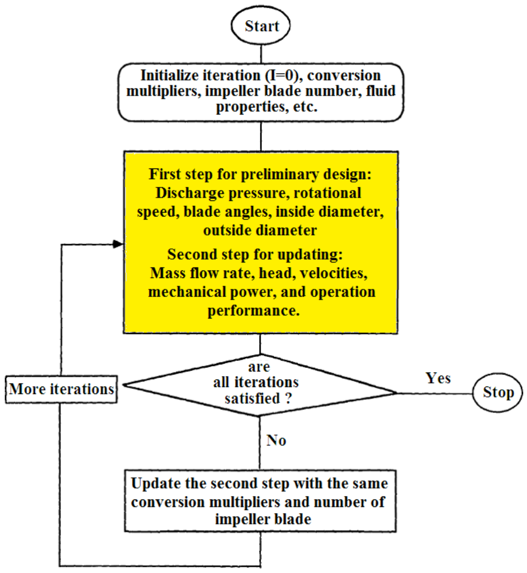

Figure 3. Calculation code procedure for preliminary design of a pump impeller model

Table 1. Important design data for a feedwater pump impeller model of RDE.

Given Parameters	**Unit**	**Value**
Thermal power of RDE core [6,7]	MW_{th}	10
Identification number	-	AP001
New impeller model type	-	Circular arc
Desired discharge pressure [6]	MPa	6
Mass flow rate of fluid [6]	kg/s	4.4
Rotational speed	rpm	1750
Density of fluid	kg/m^3	1000
Specific gravity of fluid	-	1
Acceleration of gravity	m/s^2	9.8
π constant	-	3.14

Table 2. Operation data for HTR-10 and RDE.

Given Parameters	**Unit**	**HTR-10 [11,13]**	**RDE**
Reactor thermal power	MW_{th}	10	10 [6,7]
Helium pressure	MPa	3	3 [7]
Core outlet temperature	°C	700	700 [6,7]
Core inlet temperature	°C	250	250 [6,7]
Helium mass flow rate	kg/s	4.3	4.4 [6]
Steam pressure	MPa	3.45	6 [6]
Mass flow rate of feedwater pump	kg/s	3.47	4.8 [6]
Condensate pressure	MPa	0.008	0.0027 [7]

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RESULTS AND DISCUSSION

The pump impeller was not universally designed based on standard code of manufacture. In consequence, every industry depended on its designers experience, expertise, and technical intuition to design a good pump impeller [10]. The impeller geometrical profile can only be developed by playing a vital role on the streamline flow pattern of fluid. In this study, the impeller model is preliminary designed with blade shape of circular arc as shown in Figure 2. The Table 1 lists the quantities necessary for the input data of feedwater pump impeller model. The impeller profile must be able to achieve the desirable fluid head for the discharge pressure (6 MPa) on a RDE feedwater pump. Also, it has to be developed to supply the discharge with flow capacity (4.8 kg/s). As it was mentioned in the previous section, mathematical formulation on Equations (1) to (6) can be used to determine the size and geometry of impeller model by combining dependent and independent variables as well as relative paramaters. Using the above relations, the feedwater pump head and volumetric losses can be estimated by colligating the computed fluid head in the impeller profile model. The mechanical shaft power of feedwater pump impeller can also be taken into account for determining the efficiency. The feedwater pump efficiency is the same at the rotational speed but in this preliminary design a addition of speed will result in a slight reduction in efficiency value, as declared on combination of Equations (1) and (2). The above equations are repeteadly used for calculating performance characteristics of feedwater pump so that quite tedious and time consuming. Therefore, in order to alleviate this situation the Digital Visual Fortran Edition 6.0 is used as an aid in data calculation. This Fortran software is very useful to rapidly compute the blade shape of impeller model which can yield the desired performance characteristics of feedwater pump. Figure 4 shows the validation data of Fortran code against hand calculation. It can be seen that the calculated values are very similar.

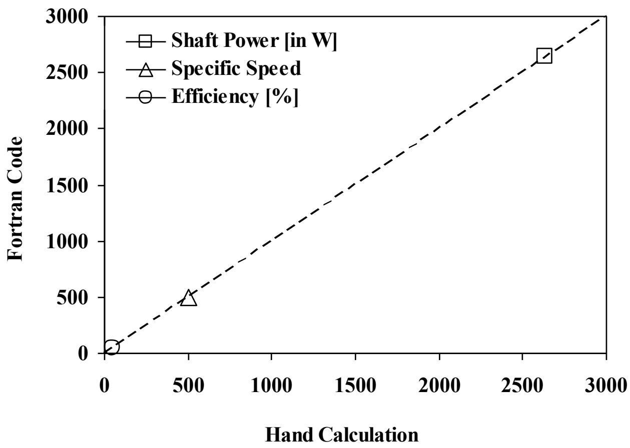

Figure 4. Comparison between Fortran code and hand calculation.

For feedwater pump of a RDE case, preliminary design of new impeller model is commenced with estimating a fluid head versus flow capacity for the desired specific speed. The next, the blade discharge angle (β_2) on impeller model is stipulated about 25 degree. A rotational speed constant or head coefficient, based on empirical correlation, is used to get the relationship between the pump total fluid head and the impeller tangential velocity. By use of the rotation speed constant, the new impeller diameter, number of blades, relative diameters of the inlet to the periphery, angle of blade at the inlet (β_1), and the geometry profile of the impeller can be calculated. This calculation is regularly based upon the Equations (1) to (6). Table 3 shows the numerical simulation results for preliminary design a new impeller model of the RDE feedwater pump. All output data in the Table 3 were obtained with a pump rotational speed of 1750 rpm, the fluid head of new impeller model is 29.1 m, and the number of blades is 5.

Table 3. The size and geometry of a new impeller for RDE feedwater pump.

Output Parameters	Unit	Value
Number of blades	-	5
Inside blade diameter	mm	81.3
Outside blade diameter	mm	275.2
Blade thickness	mm	4.7
Blade height	mm	14.1
Blade angle at inlet	degree	14.5
Blade angle at exit	degree	25
Eye diameter	mm	75.1
Volute diameter	mm	42.4
Volute length	mm	963.2

In this section, numerical simulation has been applied for the preliminary design of new impeller with number of blades 4, 5, 6, 7, 8, 9, and 10 at rotational speed of 1750 rpm and flow capacity of 4.8 kg/s. At the constantly rotational speed of motor shaft, number of blades at this impeller model have a significant effect on performance characteristics feedwater pump for a RDE case. Furthermore. the rotation speed and pressure play also an important role for computing the fluid head of new impeller as well as the efficiency of pump. The performance characteristics of the RDE feedwater pump at 1750 rpm is given in Table 4. It can be clearly seen that the preliminary design of 5-blade impeller is generating highest fluid head and efficiency (29.1 m and 52 %, respectively) as compared to the other impeller models with the different number of blades 4, 6, 7, 8, 9, and 10. At the 4-blade impeller, it appears that the generation of froth was caused by the greater amount of diffuser flow loss (about 0.195 %) occurring along the leading edge (suction side) of the blade compared to the much smaller flow along the trailing edge (discharge side). The 10-blade impeller has hydraulic loss greater than the other different blades because there is a low pressure area at the suction side of the blade inlet of the impeller and it grows continuously with increase in the number of blades. As seen in Tables 3 and 4 that the size and geometrical parameters of new impeller blade are very considered for preliminary design of a RDE feedwater pump.

Table 4. Calculated data of head, efficiency, and losses for feedwater pump impellers.

Number of Blades	Fluid Head [m]	Efficiency [%]	Hydraulic Loss [%]	Diffuser Loss [%]
4	24.5	43.6	0.14	0.195
5	29.1	52	0.17	0.158
6	27.8	49.7	0.18	0.131
7	26.6	47.6	0.19	0.112
8	23.5	42.1	0.21	0.098
9	22.7	40.6	0.23	0.087
10	21.9	39.3	0.26	0.078

The fluid flow through a new impeller blade can be described accurately in terms of curvilinear motion (as in Figure 2). The velocity analysis of the hydraulic flow is suitable to consider conditions at the inlet and exit of this impeller model. It is also convenient to treat all

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velocities such as average velocity even though this is not the case in a real flow situation. The quantities considered are the tangential velocity (u), the velocity relative to the impeller model (v_{rel}), and the absolut velocity (v) with respect to the fixed pump casing. The velocity components for feedwater pump of a RDE case can be preliminary designed by using the velocity triangle diagram in the Figure 2. Table 5 shows the calculation results of the fluid flow velocities by employing the Fortran code. The theoretical head (or Euler head) can be determined by applying the principle of angular momentum to the mass flow rate of fluid passing through the impeller blade passage. The Euler head does not account for frictional losses or non-uniform velocity effects, as shown in Equation (6). From the Table 5, it can be seen that the value of Euler head (H_E) is 60.1 m for this preliminary design of feedwater pump impeller at this RDE case. This value is used to calculate the absolut velocity and relative velocity at the inlet condition.

Table 5. Velocity results of new impeller blade for RDE.

Parameters	**Unit**	**Value**
Euler head, H_E	m	60.1
Tangential velocity at inlet, u_1	m/s	7.46
Tangential velocity at exit, u_2	m/s	25.24
Absolute velocity at inlet, v_1	m/s	-41.68*
Absolute velocity at exit, v_2	m/s	12.62
Relative velocity at inlet, $v_{1,rel}$	m/s	48.94
Relative velocity at exit, $v_{2,rel}$	m/s	14.79

* The negative sign shows the fluid flow enters to impeller blade

The calculation of the performance characteristics of feedwater pump is based on the loss correlations including hydraulic loss and diffuser loss. Although this numerical simulation of Fortran computer code is restricted to the new impeller model, the calculation results can be used as a basis to estimate the performance characteristics of the entire pump. This performance are shown in Figures 5, 6, and 7. The validity of the prediction values is also checked throughout the existing feedwater pump type of the HTR-10 and satisfactory agreement on the characteristics curves shape (ideal curves) is achieved in a RDE case. This Fortran computer code can evaluate the efficiency values estimated by a specific speed of n_s = 500. In this study, the feedwater pump is preliminary designed according to very narrow sealing gaps (radial gap clearance equal to 0.45 mm) as well as hydraulic smooth surfaces. For the feedwater pump of a RDE case, the value of the efficiency (η) is computed by using an accurate analysis on this Fortran code. Figures 5, 6, and 7 demonstrate the influence of the mass flow rate (in kg/s) on the fluid head (in m), efficiency (in %), and shaft power (in kW). As shown in those Figures, every fluid flow capacity value corresponds to a typical impeller geometry, which means that low capacity characterize more radial extended impeller while higher capacity correspond to flow respectively more axial types of impellers. Figure 7 shows the dependence of the overall efficiency on the rate of flow respectively pump size at constant rotational speed (n = 1750 rpm). It can be stated that an increase of the rate of flow leads to higher values of the overall pump efficiency, which is the effect of an increasing absolut velocity. In respect to a better comparability all results of the computations shown in the following diagrams were generated for operating conditions characterized by a flow rate of 4.8 kg/s (at RDE case) and a speed of rotation 1750 rpm.

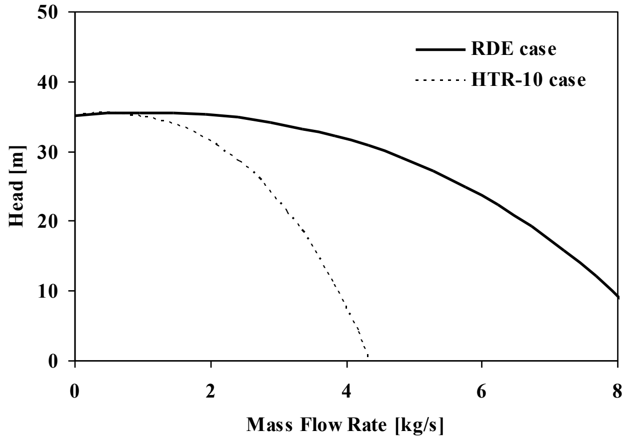

Figure 5. Fluid head of a feedwater pump impeller model at 1750 rpm

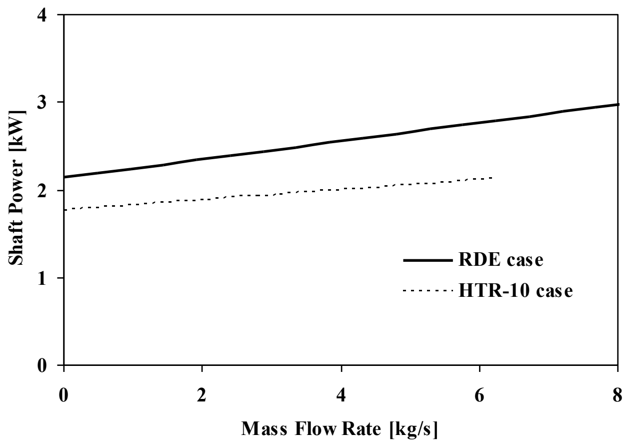

Figure 6. Shaft power of a feedwater pump impeller model at 1750 rpm

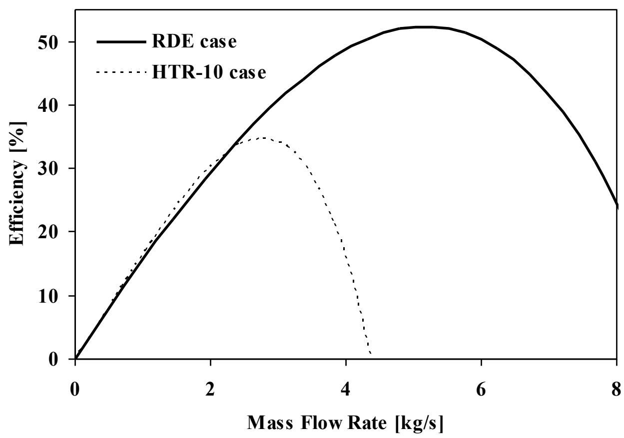

Figure 7. Efficiency of a feedwater pump impeller model at 1750 rpm

The calculation iteration procedure, shown in Fig. 3, is performed for determining the values of mass flow rate, fluid head, efficiency, and power. In this paper, the optimal values of hydraulic

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losses and diffuser losses are obtained for a highest efficiency (η) of feedwater pump under the design mass flow rate (Q = 4.8 kg/s) and fluid head of impeller (H = 29.1 m). The highest efficiency operation point is 52 % for 5-blades as on Table 4 and Figure 7. In this condition, the values of hydraulic and diffuser losses are 0.17 % and 0.158 %, respectively. It can also be seen in the Table 4 that the increasing the number of blades leads to increased hydraulic losses and decreased diffuser losses. In this preliminary design, performance characteristics of RDE feedwater pump impeller have been evaluated on the same impeller diameter (d = 275.2 mm) having different number of blades. In the case of pump impeller with 4-blades, the number of blades used is too few so that it is obtained the increasing of diffuser losses value (D_L = 0.195 %). Thus, it should be used at least 5-blades.

CONCLUSION

The preliminary design of a feedwater pump impeller model for RDE by using Fortran code have been performed. From the calculation results, it can be concluded that this code provides in a more accuration on preliminary design of a feedwater pump impeller model, compared with hand calculations (the validation in Fig.4). Given the number of impeller blade (5-blades) established, the code computes the performance characteristics such as the values of fluid head (29.1 m), shaft power (2.64 kW), and mass flow rate (4.8 kg/s) for the highest efficiency (52 %) operation point of a feedwater pump impeller model. For rotational speed of 1750 rpm indicates, size and geometry of impeller blade model have inlet angle 14.5 degrees, exit angle 25 degrees, inside diameter of 81.3 mm, outside diameter of 275.2 mm, thickness of 4.7 mm, and height of 14.1 mm.

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APPENDIX

1. Specific speed of a pump is commonly defined by the following equation (in US unit):

$$n_s = \frac{n\sqrt{Q}}{H^{0.75}}$$

where n_s is specific speed in dimensionless, n is rotational speed of impeller in 1 rpm, Q is volume flow rate in 1 gpm (1 gpm = 3.785 liters/m), and H is fluid head in 1 ft.
The unit of this equation is convert into SI unit, hence: US $n_s = K_0\ n_s$ [in SI unit], where K_0=1.63, n_s is specific speed in dimensionless, n is rotational speed of impeller in rpm, Q is mass flow rate in kg/s, and H is fluid head in m. From the Equation (1) of Reference (15), it can be obtained the relationship of similar formula:

$$n_s = \frac{K_1\sqrt{Q}}{H^{0.75}}$$

with $K_1 = K_0\ n$ and n = 1750 rpm (for current paper).

2. The equation (9) of reference (15) shows:

$$\eta = \frac{\rho\, g\, Q\, H}{P_{sh}}\, x\, 100$$

where η is feedwater pump efficiency (in %), ρ is fluid density of water (in kg/m^3), Q is volume flow rate (in m^3/s), H is fluid flow (in m), g is the acceleration of gravity, and P_{sh} is shaft power (in W). For current paper, it is written in the Equation (2) where η the feedwater pump efficiency in dimensionless, γ is specific weight of fluid in N/m^3 ($\gamma = \rho\ x\ g$), and unit conversion K_2 = 1.0 x 10^6 with P_{sh} in kW and Q in kg/s.

3. For steady state condition, the continuity equation (1) of reference (16) shows:

$$V = \omega\, r$$

where V is absolute velocity (in m/s), ω (= 2 $\pi\, n$) is angular speed of impeller (in rps), and r is impeller radius (in m). It is similar to the equation (4) of reference (17) with u is velocity (in m/s), n is rotation speed of impeller (in rps), and d is impeller diameter (in m).

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4. Hydraulic losses (H_L in %) is calculated by:

$$H_L = \frac{Q_L}{Q_S} x100\,\%$$

where Q_L (= ρ A $(2\ g\ H)^{0.5}$) is mass flow rate of internal leakage in kg/s and Q_S (= ρ A u) is mass flow rate at impeller blade in kg/s.

5. Diffuser losses (D_L in %) is calculated by:

$$D_L = \frac{Q}{Z\,n\,d^3} x100\,\%$$

where Z is the number of blades at pump impeller.