Study of RFD Model Spectrum and the Characteristic Conversion Methods

in Industry

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Abstract: Reversed Flow Diverter (RFD) is a type of maintenance-free device which is applied in pumping and delivering hazardous fluid by using fluidic power. Because of including no moving parts, the operating efficiency and characteristics of RFD are especially sensitive to the structure and operating parameters of the device. This paper presents an optimization design method of RFD based on Genetic Algorithm (GA). System scale and efficiency have been both considered by designing specific fitness function. Based on serialized optimum designs, an example of RFD model spectrum is promoted. Our customers can easily choose a proper type of RFD according to certain flow and head as well as predict the operating of RFD. In the end, the paper discusses the influence of physical characteristics of the delivered fluid. The conversion method of operating flow and efficiency of RFD system is studied.

Key words: RFD; optimization design; operating prediction; model spectrum; genetic algorithm

1 Overview

RFD is a type of fluidic power device designed by the theory of jet. Without moving part, RFD can avoid wear and operate with low maintenance, thus it can be used in occasions where human is inaccessible. RFD is composed of a jet pair, an air-liquid charge vessel and a fluid delivery unit (Fig. 1.). The switching operating jet pair generates compressed air and by the air turns the energy into the pulse liquid with the charge vessel, and then by reversing flow of RFD, the liquid is delivered to outlet. Periodic conveying process is generally divided into two phases, i.e., refill phase and driving phase. Compared with other maintenance-free devices, RFD shows advantages in low waste gas emission, strong adaptability to operating temperature, medium and pressure, et.al.. So it is believed to have a great potential market in the nuclear post-processing industry.^{[1]-[4][12][13]}

Although the structure of RFD is relatively simple, the power of fluidic driven system makes the operating conditions complex and the operating parameters sensitive to the fluidic components. Generally, the industrialization is too expensive for this technology. In China, the serialized design is the key point that influences the application of the technology in nuclear reprocessing facilities and other involved fields. In the late 1980s, AEA almost monopolized this technology and successfully applied it in nuclear post-processing. But due to the complexity and sensitivity of the technology, the key point is still unpublished. What's more, the industry application depends too much on field tests. Serialized design for industry has not completed yet. As the investment in nuclear industry has been cut down nearly all over the word, the relevant study has been suspended. However, the independent study in our country has been going on constantly since 1990s. It has not been universally applicated for now. The main obstacle comes from the restriction of complicated theory. Therefore, considering the related design theory and equipment test have been done already, serial model spectrum should be provided, besides, a more developed operating prediction program should be served instead of industrial tests. ^{[7]-[10][11][14]} In order to achieve industrialization as soon as possible, this paper, based on the study of the GA optimization design, makes serialized design of the RFD system as shown in Fig. 2..



Fig. 1. Schematic construction diagram of RFD set Fig. 2. Calculation sketch of RFD set

2 Theory

2.1 Optimization design model

The optimization of RFD is to achieve the best delivery performance with the smallest set. In a multi-objective problem, customers need to balance their needs. Generally, industrial applications focus on operating and consider the system scale at the same time. Specifically in this paper, to find a valid solution which meets the customer for flow, head, and the limiting conditions, a compound optimization criterion is proposed as:

$$K = N / T^n \tag{1}$$

where N stands for the system efficiency, T for the operating period, a measure of the system scale, n for the scale index ranging from 0 to 1. In the criterion, the smaller the scale index is, the smaller the change rate of the denominator is when T changes, which means the impact of scale is smaller. A larger K indicates that the design can not only satisfy the application goals

(flow, head, size), but also achieve high efficiency. In this way, this multi-objective problem is simplified to a single one with this compound criterion.^{[5][6]}

According to the RFD hydraulic model and the optimization goal, W and M respectively stand for the system operating and scale, numerical simulations and tests experience show that parameters required optimized are as follows: diameter D_{pc} and height H_{pc} of the charge vessel, RFD immersion depth H_f , driving pressure P_i , refill pressure P_r , nozzle diameter D_t and discharge pipe diameter D_o . These parameters are set in domains based on practical industry application, with limits of the parameters matching each other as well. To achieve the highest efficiency and the smallest system while meeting the flow rate, the model is set as:

$$\max W = \max f(D_{pc}, h_{pc}, h_f, P_i, P_r, d_t, d_o)$$

$$\min M = \min f(D_{pc}, h_{pc}, h_f, P_i, P_r, d_t, d_o)$$

s. t.
$$\begin{cases} 0 < D_{pc} <= 2000 \text{mm} \\ 0 < h_{pc} <= 5 \text{m} \\ 0.2 < h_{f} <= 5 \text{m} \\ 1 < P_{i} <= 10 \text{atm} \\ -1 =< P_{r} < 0 \text{atm} \\ 0 < d_{t} <= 100 \text{mm} \\ d_{o} >= d_{t} \end{cases}$$
(2)

2.2 Process of genetic algorithm optimization design

In order to use genetic algorithm to solve this multi-factor problem, a fitness function based on RFD optimization model is needed. To optimize those parameters with the given Q, H and n, the GA fitness function is written as follows: (1) set the viscosity N_u , density ρ , coefficients C_p , C_{drf} , C_d , g, k, lengths of inlet and outlet pipelines L_r and L_o , head H, scale index n, average flow rate Q and other known parameters; (2) read a current individual produced by the GA box, i.e., a group of optimized variables: H_f , D_o , D_i , H_{pc} , D_{pc} , P_i , P_r ; (3) judge if the variables match the parameters limits, if not, assign 1000 to fitness and then end the program; (4) calculate the operating parameters and judge if they satisfy the pulse period, head, et.al., if not, assign 900 to fitness and then end the program; (5) calculate flow Q_i and Q_o of the inlet and outlet nozzles in the driving phase, the average flow Q_{ra} , and hydraulic efficiency N_h over a period, assign 800 to fitness; (6) judge if Q_{ra} , Q_o/Q_{ra} , H_{pc}/D_{pc} , period T, delivery line loss, and backflow ratio are kept in the predefined limits, and set fitness according to the following principles: 1) if the average flow Q_{ra} is between $Q \pm 0.1 \text{m}^3/\text{h}$, set fitness value as 700; 2) if term 1) is met and Q_o/Q_{ra} is between $0.9 \sim 1.1$, set fitness as 600; 3) if term 2) is met and delivery line loss is lower than 15% of H, set fitness as 500; 4) if term 3) is met and H_{pc}/D_{pc} is between 2.5 to 3.5, set fitness as 400, 5) if term 4) is met and *T* is less than 1000 seconds, set fitness as 300; 6) if term5) is met and backflow ratio is greater than 8, the solution is considered to be valid, then calculate the compound optimization criterion *K* and assign it to the fitness.

When fitness values of the current generation are calculated, selection, crossover and mutation operations are used to produce the next generation. Then fitness of the new generation is calculated. That cycle repeats and finally a proper group of optimized variables is obtained.

Some information should be input before running the GA program, which includes crossover probability, mutation probability, population size, length of chromosome, the generation gap, the maximum generation, et.al.. Those parameters affect the operating and even influence the convergence of the algorithm. In this paper, gauss mutation is adopt; population size, which directly affects the calculation efficiency and convergence of GA is generally between 10 to 200, in this paper, it is set 200 based on tests; and the maximum generation, acting as a termination condition of algorithm, is set as 2000.Because of the way of random search, GA shows great advantage in CPU comsumption. It takes only about 100 seconds to calculate one case on the current mainstream computer, which makes the serialized design for industrial production possible. However, if one certain case is calculated several times, there will be some small deviation between the results due to the randomness. But compared with basic GA, by debugging control parameters, stability and convergence can be satisfied in industry, also, it seldom results in an local extremum. As shown in Fig. 3., the point near global extreme point appeared at 600 steps, and points got very close to the true value after 600 steps when the algorithm performance was greatly improved.



Fig. 3. The best and average fitness values of each generation in GA

By this program we can design for the various parameters and find out the matching of

structure and operating parameters, as well as the effects of parameters on the operating. The model spectrum based on serialized design can also be figured out to provide basic parameters for RFD model design.

3 Results

3.1 The optimization design results

In the calculation the resistance coefficients involved include pressure recovery coefficient of diffusion tube, nozzle suction-flow coefficient, total resistance coefficient of delivery pipe, and nozzle flow coefficient. The scale index *n* is set 0.1, for a relatively large system scale. In the paper, 68 cases are calculated with the head ranging from 3 to 30 meters and average flow from 1 to 20 m³/h. Through single factor experiments about nozzle diameter D_t , delivery pipe diameter D_o , charge vessel diameter, and height and driving pressure P_i , the following qualitative conclusions are reached.

Firstly, when the head is fixed and the required flow increases, P_i hardly change, but RFD nozzle diameter D_t , delivery pipe diameter D_o , charge vessel diameter D_{pc} and height H_{pc} , and other parameters related with scale will increase. Otherwise, it is bound to result in an increase in hydraulic loss and a decrease in efficiency of RFD, even lead to the cavitation and a system failure. When the flow is fixed and the head increases, driving pressure P_i increases; while RFD nozzle diameter D_t and delivery pipe diameter D_o are crucial parameters of the delivery capacity, i.e., flow rate, nearly remain unchanged. That means, the way RFD structure parameters impact the operating is that, cross-section diameters (such as: D_t , D_o , D_{pc}) decide the flow rate, driving pressure P_i decides the head. Since the charge vessel is similar to a gas-liquid piston pump, it is reasonable that it is close to conventional piston pump. In addition, within the limits of parameters and all the cases calculated, the refill pressure holds steady at - 5 mH₂O.

Secondly, when the flow and head are fixed and the scale index n increases, scale parameters decrease and system efficiency N also decreases. Customers can choose an appropriate scale index to fit their equipment room.

Summarizing the optimization results of 68 cases we get regression equations of the above relationships, shown in table 1 as empirical formulas, which can be referred when choosing an optimal model.

Table 1 Empirical formulas for RFD optimization design	
The known average flow rate $Q(m3/h)$, $H(m)$	Applicable
	condition
delivery pipe diameter: Do=37.932Q0.4151 (mm)	Pr=-5m
nozzle diameter: Dt=9.668Q0.4966 (mm)	Q:1~20m3/h
charge vessel height Hpc: Hpc=0.5584H0.3Q0.27 (m)	H:3~30m (n=0.1)
charge vessel diameter Dpc: Dpc=Hpc/2.5 (m)	
driving pressure: Pi=0.1463H+0.0175(atm)	

3.2 Model Spectrum design

High efficiency range is important for all kinds of pumps including RFD. To satisfy application, it is necessary to study the high efficiency range and the performance curve of RFD. For RFD pump, head H is both operating parameter and structure parameter, so if H is set as a GA optimized variable and the other parameters exclude Q are all fixed, the algorithm will select out a H - Q match of high efficiency and then a high efficiency range can be worked out soon. In this paper, 25 RFD models are set corresponding to a certain H-Q range, and their high efficiency ranges are calculated out and gathered up to draw the RFD model spectrum as shown in Fig. 4..



Fig. 4. RFD model spectrum

In application, customers can choose a suitable model shown in Fig. 4. according to flow and head, with supporting structure and operation parameters.

3.3 Performance prediction curve

For a certain RFD model, the paper also studied flow and efficiency change with head in normal operating condition. According to calculation results, the curve Q vs H, N vs H are shown as below: (model $D_t 20 - P_i 3$ for example)



Fig. 5. RFD head H vs flow Q

Fig. 6. RFD efficiency N vs flow Q

The H-Q curve shows that RFD performance curve is a quadratic parabolic, similar to the centrifugal pump. In Fig. 6., N-Q curve between the two vertical is the high efficiency range shown in RFD model spectrum, where not only the efficiency reaches the highest, but also the optimal control conditions in fitness function are satisfied. When Q is too low and H is too high, injection will inevitably occur, when Q is too high and H is too low, line loss will increase and lead to the decrease of the system efficiency.

3.4 Performance conversion methods for medium characteristics

When studying prediction curve of performance of a certain RFD model, different kinds of liquid should influence the operating (flow and efficiency), because they have different viscosity and density compared with water. Set model $D_t 20 - P_i 3$ as an example, comprehensive diagrams of density and viscosity vs flow and efficiency are shown as Fig. 7. and Fig. 8.. The figures show that when changing the kinematic viscosity within the scope of a relatively low level (1e-6~1e-4 m²/s), as the density and viscosity increases, the efficiency firstly increases and then decreases, which means there is an optimal combination range for density and viscosity is slight overall. When the efficiency reaches the maximum, the viscosity change nearly makes no difference. The flow decrease with viscosity increasing is also small, but with the increase of density, the average flow with a fixed head shows an obvious trend of decline.

1) As the density and viscosity increase at the same time, the hydraulic efficiency shows a decrease after an increase, which means there is a maximum efficiency when flow changes. In the efficiency decreasing phase, delivering resistance (such as energy dissipation in the form of friction) increases as the liquid viscosity increases.

2) There are economic velocities at all density levels, where hydraulic efficiency reaches highest and the viscosity affects little.

3) As the density increases, the flow decreases, and viscosity increases, the flow shows a decreasing trend which is not significant.

4) In industry, attention need to be paid to the decreasing of flow and efficiency when delivering fluid of high viscosity.



Fig. 7. Effects of Density and viscosity on flow rate



Fig. 8. Effects of Density and Viscosity on efficiency

3.5 Optimization design with medium characteristics considered

In industry, particular designs for RFD devices applied in special delivered mediums are needed. The paper studied the change of structure and operation parameters of the optimized RFD model with different liquid and the same flow and head. For example, setting the flow as $5 \text{ m}^3/\text{h}$, head as 15 m, scale index *n* as 0.5, and with changing the density and viscosity based on water, the optimized parameters of RFD device will change.

Analyze the results and conclusions are as follows:

1) While setting the flow constant and increasing liquid density, driving pressure P_i need to increase to maintain the head, otherwise the needed pressure or head can not be reached and it will be unable to meet the flow rate.

2) As to RFD model design, scale parameters show an increasing trend as the density and viscosity increase. When flow keeps constant, nozzle diameter D_t basically remains unchanged.

3) When the delivered water is $30 \sim 60^{\circ}$ C in the experiments, it is found that the viscosity changes slightly along with temperature changes, and flow rates remains the same, which has been confirmed in RFD device test.

4 Conclusions

In this paper, an optimization design program of RFD based on GA have been developed, based on single factor tests for structure and operation parameters, the influence laws of parameters on the operating have been found out, and according to a typical range of flow and head in industry, 25 RFD models have been designed to establish a model spectrum with a form of the device parameters. The prediction of performance has also been given out. And the influence of viscosity and density of the delivered liquid, the conversion rules for performance, and the law of liquid characteristics on the optimization design have also been studied.

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