Journal of Mechanical Science and Technology 24 (2010) 185~188
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-009-1138-1

# Prediction of the resistance coefficient in a segment ball valve †

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(Manuscript Received May 4, 2009; Revised September 22, 2009; Accepted October 12, 2009)

**Abstract**

This study presents a numerical approach to predict the flow resistance coefficient in a segment ball valve. If more than a few valves are installed in a pipe system, the flow resistance coefficient should be considered in selecting the valves. Thus, the design of a segment ball valve incorporating the prediction of the flow resistance coefficient is suggested in this study. A segment ball valve incorporates the advantages of a ball valve and a butterfly valve. To predict the flow resistance coefficient of a segment ball valve, two approximate methods are introduced: second-order response surface method (RSM) and kriging interpolation method. The metamodels, built by EXCEL program and determined from the two models, were compared with the true numerical model. This study proposes the most suitable approximation method for the prediction of the flow resistance coefficient in a design of valve.

*Keywords*: Ball valve; Flow coefficient; Flow resistance coefficient; Kriging interpolation method; Response surface method

## 1. Introduction

A valve is a device that regulates the flow or the pressure in a fluid flow or pressure system. This regulation may involve the stopping and starting of flow, flow rate control, flow diversion, back flow prevention, pressure control, or pressure relief [1]. A ball valve consists of a ball placed in the passageway through which fluid flows. When a ball closes the passageway, the seat seals the ball valve. The operating principle of a ball valve is similar to that of a butterfly valve. In general, ball valves are installed in a pipe system where tight shut off is required. However, they have relatively large end-to-end dimensions. On the other hand, butterfly valves offer the advantages of compact size due to their smaller end-to-end dimensions. Thus, a segment ball valve integrating the advantages of the aforementioned types of valves has been devised.

This study presents the numerical approach to predict the flow resistance coefficient generated in a segment ball valve. The investigated valve is an on-off valve to control the stopping and starting of flow.

If several valves are installed in a pipe system, the flow resistance coefficient should be considered in valve selection, that is, the flow coefficient should be adopted as the criterion of valve selection. The flow coefficient and the flow resistance coefficient are inversely proportional to each other. Thus, for simplicity, the flow resistance coefficient was utilized.

The flow coefficient, $C_v$, states the flow capacity of a valve in gal/min of water at a temperature of 60°F for a pressure loss of $1lb/in^2$ at a specific opening position [1]. To calculate the flow resistance coefficient, we performed the analysis of fluid flow for a full open valve.

In this study, two approximate methods were investigated to predict the flow resistance coefficient: the second-order response surface method (RSM) [2] and the kriging interpolation method [3-5]. The metamodels determined from the two methods were compared with the true numerical model. In this study, the ANSYS CFX [6] program was utilized for the numerical analysis of fluid flow.

## 2. Segment ball valve

A segment ball valve consists of a partial ball, body, stem and seat, as shown Fig. 1. Since a segment ball valve has small end-to-end dimensions, it can be installed in narrow spaces in a pipe system. When a segment ball is in full open

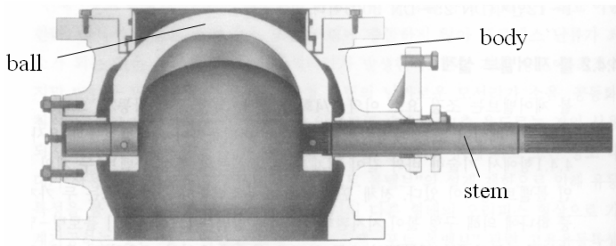


Fig. 1. Segment ball valve.

† This paper was presented at the ICMDT 2009, Jeju, Korea, June 2009. This paper was recommended for publication in revised form by Guest Editors Sung-Lim Ko, Keiichi Watanuki.

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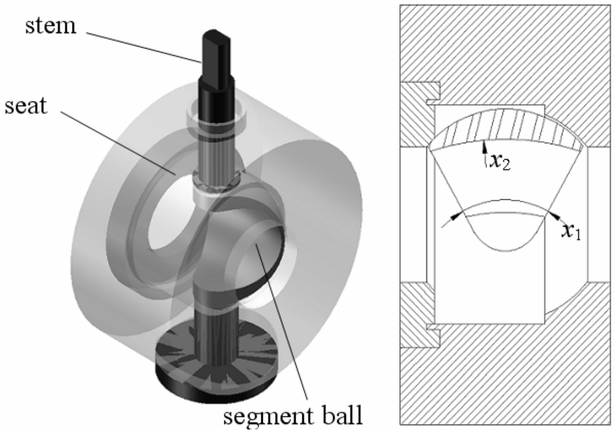


Fig. 2. Design variables for design of segment ball.

position, it is fully out of the passageway through which the fluid flows. In general, a butterfly valve has a flow resistance coefficient of 0.2~1.5 in a turbulent flow, while a ball valve has 0.1 [7]. In this study, we investigated the on-off segment ball valve.

## 3. Kriging interpolation method

Kriging is a method of interpolation named after a South African mining engineer D. G. Krige, who developed the technique while trying to increase accuracy in predicting ore reserves. In the kriging model, the global approximation model for a response $y(\mathbf{x})$ is represented as

$$y(\mathbf{x})=\beta+v(\mathbf{x}), \tag{1}$$

where $\mathbf{x}$ is the design variable vector, $\beta$ is a constant, and $v(\mathbf{x})$ is the realization of a stochastic process. In Eq. (1), $v(\mathbf{x})$ has the mean zero, variance $\sigma^2$, and non-zero covariance. The flow resistance coefficient $\zeta$ is replaced by $y(\mathbf{x})$ to make a surrogate approximation model.

Let $\hat{y}(\mathbf{x})$ be an approximation model. Hereafter, ^ means the estimator. When the mean squared error between $y(\mathbf{x})$ and $\hat{y}(\mathbf{x})$ is minimized, $\hat{y}(\mathbf{x})$ becomes

$$\hat{y}(\mathbf{x}) = \hat{\beta} + \mathbf{r}^T(\mathbf{x})\mathbf{R}^{-1}(\mathbf{y} - \hat{\beta}\mathbf{q}) \tag{2}$$

where $\mathbf{r}$ is the correlation vector, $\mathbf{R}$ is the correlation matrix, $\mathbf{y}$ is the observed data and $\mathbf{q}$ is the unit vector. The definitions of $\mathbf{R}$ and $\mathbf{r}$ are well explained in Refs [3-5].

The unknown correlation parameters of $\theta_1, \theta_2, \ldots, \theta_n$ defined in $\mathbf{R}$ are calculated from the formulation according to

$$\text{maximize} \quad -\frac{[n_s ln(\hat{\sigma}^2) + ln|\mathbf{R}|]}{2}, \tag{3}$$

where $\theta_i$ (i=1,2,…,$n$) > 0. In this study, GRG (generalized reduced gradient) algorithm built in the EXCEL program was utilized to determine the optimum parameters. To assess the kriging model, the error in surrogate model can be measured by

Table 1. The bounds of each design variable.

| | | |
|---|---|---|
| $x_1$ (segment angle) | Upper bound | 64.5° |
| | Lower bound | 56° |
| $x_2$ (radius of curvature) | Upper bound | 100 mm |
| | Lower bound | 80 mm |

$$Average\ \%error = \frac{1}{n_t}\sum_{i=1}^{n_t}\left|\frac{\hat{y}_i - y_i}{y_i}\right| \times 100 \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n_t}\sum_{i=1}^{n_t}(y_i - \hat{y}_i)^2} \tag{5}$$

where $n_t$ is the number of sample points for validation, which is set to 10 in this study.

## 4. Prediction of the flow resistance coefficient

### *4.1 Design of the segment ball valve*

For the design of the segment ball valve, the design variables were set up as $\mathbf{x}=[x_1, x_2]^T$, where $x_1$, and $x_2$ are the segmenting angle and the radius of curvature inside the segment ball, respectively (Fig. 2). The flow resistance coefficient was related to the shape of the segment ball. The values of the upper bound and lower bound are shown in Table 1. The lower bound of $x_1$ represents the minimum value that can seal the valve.

The design process of a segment ball valve for prediction of the flow resistance coefficient is as follows:

Step 1. DOE strategy

First, sample points should be set up to obtain the metamodel of flow resistance coefficient. DOE strategies can be used to sample the design space. In this study, the Latin hypercube design (LHD) was introduced to sample the design space. The sample points were generated by minimizing Eq. (6) [8-9].

$$\text{Minimize} \quad \sum_{i=1}^{n_s}\sum_{j=i+1}^{n_s}\frac{1}{d_{ij}} \tag{6}$$

where $n_s$ is the number of sample points, and $d_{ij}$ refers to the distance between points $i$ and $j$.

Step 2. Matrix experiment

The responses of the flow resistance coefficient were calculated for each row of matrix experiments. The number of experiments was identical to the number of rows in the matrix; that is, an experiment equaled one fluid flow analysis.

Step 3. Building and validation of metamodels

Based on the responses calculated from Step 2, the second-order RSM and the kriging models were constructed. To access the metamodels, the error in the surrogate model was characterized by using a few metrics.

### 4.2 Fluid analysis

Numerical analysis of fluid flow was performed to obtain flow resistance coefficients according to the shape of the segment ball. For fluid analysis of segment ball angle of 90°, a grid was structured by ANSYS CFX-mesh at $\alpha$=90°, as shown in Fig. 3. The grid of about 95 000 nodes and 307 000 elements is shown in Fig. 4. The value of $\alpha$ ranged from 0° to 90°. The segment ball valve was fully closed at $\alpha$=0° and fully open at $\alpha$=90°.

Since a velocity profile develops before the fluid reaches the valve, the distance required for the flow to develop may be estimated by using an empirical formula for entry length $L_e$, given by $L_e/D$=4.4 $(Re_D)^{1/6}$. This correlation predicts lengths of approximately 33 $D$. The length of the upstream is 33 $D$ and that of the downstream is 11 $D$, as shown in Fig. 3 [10]. The length is the distance from the shaft of the segment ball to upstream or downstream. The diameter $D$ of pipe was 50 mm. The fluid passing through the valve was water. Its incoming velocity was 3 m/s density $\rho$ was 997.4 kg/m$^3$, and dynamics viscosity $\mu$ was 0.8899$\times$ 10$^{-3}$ kg/m·s. In this study, the assumptions for fluid analysis were as follows:

· The flow is steady-state and three-dimensional,
· The fluid is Newtonian and incompressible, and
· The walls of the pipe and valve are smooth.

The boundary conditions were as follows:

· The uniform inlet velocity **w** is 3m/s, and the outlet condition is 0.1013MPa (1 atm),
· Turbulence model is $k$-$\varepsilon$,
· The wall condition of valve and pipes is No-slip and Smoothing and
· For the rest of boundary conditions, the default values built in ANSYS CFX are utilized.

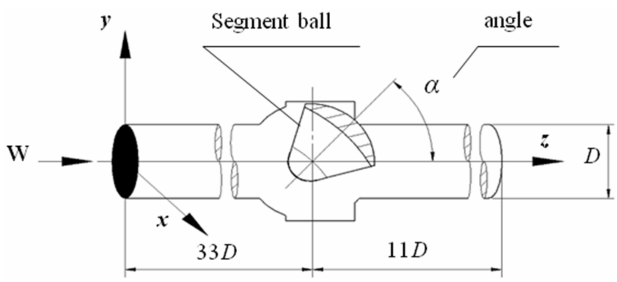


Fig. 3. Simplified numerical model of segment ball valve.

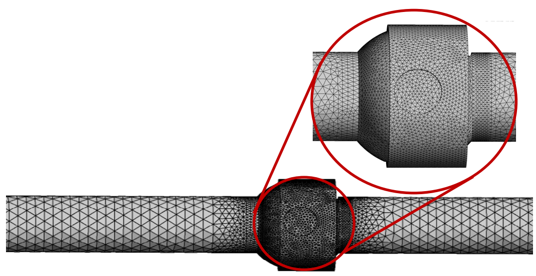

Fig. 4. Grid of numerical model.

### 4.3 Calculation of the flow resistance coefficient

The flow resistance coefficient, $\zeta$, defines the friction loss attributable to a valve in a pipeline in terms of velocity head or velocity pressure, as expressed by the Eqs. (7)-(9) [1]

$$\Delta P = \zeta \frac{v^2 \rho}{2} \tag{7}$$

$$\zeta = \frac{\Delta P}{1/2 v^2 \rho} \tag{8}$$

$$\Delta P = P_1 - P_2 \tag{9}$$

where $P_1$ and $P_2$ are the static pressures taken at upstream and downstream, respectively, $v$ is average velocity (m/s) in a pipe line, and $\rho$ is density (kg/m$^3$) of fluid. Figure 5 shows that the measuring section of $P_1$ is 2 $D$ away and that of $P_2$ is 6 $D$ away from the shaft of the segment ball [11].

## 5. Results

To build each metamodel, the sample points of $n_s$=50 were obtained by applying Eq. (6). The design points defined by the Latin hypercube design are represented in Table 2. Fluid analyses were performed for $n_s$=50. The responses of the flow resistance coefficient calculated from the ANSYS CFX are summarized in Table 2.

Based on these values, the response surface model and the kriging model were constructed for the flow resistance coefficient. The second-order response surface model was obtained by Eq. (10).

Table 2. Analysis results of the sample points using LHD.

| EXP. No. | Segment angle ($x_1$, °) | Radius of curvature ($x_2$, mm) | Flow resistance coefficient ($\zeta$) |
|---|---|---|---|
| 1 | 58.151 | 94.676 | 0.173 |
| 2 | 64.242 | 94.838 | 0.241 |
| … | …. | … | … |
| 49 | 57.946 | 87.648 | 0.176 |
| 50 | 60.101 | 99.918 | 0.183 |

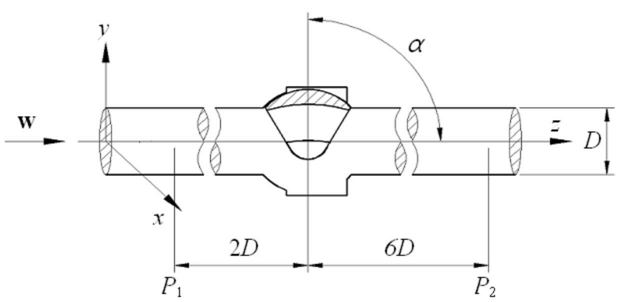


Fig. 5. Position of $P_1$ and $P_2$ for calculating $\zeta$.

Table 3. Optimum parameters of $\theta$ and $\beta$.

| | | |
|---|---|---|
| $\hat{\zeta}(x_1, x_2)$ | $\theta_1^*$ | 1.921 |
| | $\theta_2^*$ | 12.488 |
| | $\beta^*$ | 0.203 |

Table 4. Validation of RSM and kriging models.

| EXP. No. | $x_1$(°) | $x_2$(mm) | Flow resistance coefficient ($\zeta$) | | |
|---|---|---|---|---|---|
| | | | Analysis | RSM | Kriging |
| 1 | 58.372 | 93.812 | 0.180 | 0.176 | 0.170 |
| 2 | 59.598 | 99.756 | 0.186 | 0.181 | 0.180 |
| 3 | 56.314 | 90.268 | 0.175 | 0.172 | 0.174 |
| ... | ... | ... | ... | ... | ... |
| 8 | 58.787 | 87.882 | 0.183 | 0.180 | 0.180 |
| 9 | 62.293 | 88.622 | 0.218 | 0.215 | 0.216 |
| 10 | 63.522 | 97.816 | 0.232 | 0.229 | 0.232 |
| RMSE | | | | 0.004 | 0.007 |
| Average %Error | | | | 2.07% | 2.54% |

$$\begin{aligned}\hat{y} &= 3.64441 - 0.12841x_1 + 0.33659\times10^{-2}x_2 \\ &+0.11730\times10^{-2}x_1^2 - 0.40597\times10^{-4}x_1x_2 \\ &- 0.07196\times10^{-4}x_2^2\end{aligned} \tag{10}$$

For the kriging metamodel, the optimum parameters of $\theta_1$ and $\theta_2$ were determined by solving Eq. (3). Their values and the optimum of $\beta$ are depicted in Table 3. The GRG method is an algorithm finding a local optimum. Thus, the optimum was investigated by changing 10 pieces of initial values. The result showed the same optimum was calculated. Table 4 shows the errors of Eqs. (4-5) generated in the metamodels.

## 6. Conclusions

The present study proposes a prediction method of the flow resistance coefficient that can be applied to a segment ball valve design. The response surface model (RSM) and the kriging method were used as the metamodel techniques.

This study shows that the RSM is more suitable than the kriging model in predicting the flow resistance coefficient of a segment ball valve because the response of the flow resistance coefficient is a highly nonlinear function with noises.

The metamodel determined from this study can be applied to the design of a segment ball valve. A study on actual application is left for the future work.

## Acknowledgment

This work was supported by the Valve Center of the Regional Innovation Center (RIC) Program of the Ministry of Knowledge Economy (MKE).

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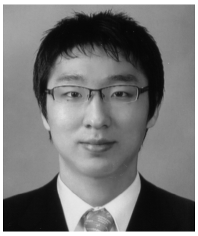

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