ABSTRACT

Solenoid operated valve (SOV) is widely used in many applications due to its fast dynamic response, cost effective, and less contamination sensitive characteristics. All of instrumental SOVs used in nuclear power plants (NPP) in Korea are imported from foreign companies and not localized mainly because of lack of design technology and reliability. In this paper, we have established detailed procedure of designing SOVs for special applications such as NPP where are in most harsh environmental conditions. The design process suggested have been verified with theoretical relations and experimental results with some prototypes of the SOVs, which include physical dimension of solenoid coil and electromagnetic properties such as coil resistance and attraction force of the solenoid actuator. Good agreement of designed results with the verified parameters gives the reliability of our design methodology.

1 INTRODUCTION

A solenoid is an electromagnetic device in which a coil of wire (8 in Fig. 1) surrounds a steel rod (10 in Fig. 1) and induces a magnetic field that moves the rod (10 in Fig. 1) into and out of the coil [1]. The solenoid operated valve (SOV) in Fig. 1 is a valve in which the actuation occurs by passing an electric current through a circular coil that is concentric to a cylindrical steel core and/or plunger [2]. The current running through the coil generates a magnetic potential difference across the air gap. This magnetic potential difference produces an attractive force between the opposing core and plunger, which moves the plunger to cause closing or opening of the valve. A solenoid valve is a combination of two basic components. One is a solenoid that consists of coil and a magnetic plunger (or core), and another is valve body containing an orifice (7 in Fig. 1) in which a valve disc (11 in Fig. 1) is positioned to stop or allow flow. These SOVs are widely used to control fluid flow in almost every industrial field, including use in nuclear power plants (NPP).

There are various types of solenoid valves used in industrial applications. They can be classified according to port number (2-way, 3-way, or 4-way), operation mechanism (direct-acting or pilot operated), usage purpose (instrumental or process), etc. There are special valves that are used in harsh environments, such as those encountered in NPPs, cryogenic
facilities, and chemical plants. The 2-way solenoid valve has one inlet and one outlet pipe connection. The normally open type valve is open when de-energized and closed when energized. The 3-way valve has three pipe connections (pressure, cylinder, and exhaust port) and two orifices. The normally closed 3-way type valve applies pressure through the cylinder port when the solenoid is energized and exhausts pressure through the exhaust port when the solenoid is de-energized. The pilot operated-solenoid valve has a pilot and bleed orifice that enables this valve to use line pressure to assist the valve in its operation. This pilot solenoid valve is suited for high or moderate flow and quick exhaust applications in power plants. Of these types of SOVs, safety function-related SOVs require various cautions and considerations when new models are developed and used, because they are usually used to protect machinery or entire plant systems from severe accidents or to mitigate the consequences of accidents. Therefore, the safety-related SOV has to meet various requirements with respect to its design and manufacture. In addition, it must be reliable under the most stringent environmental conditions, such as high temperature, humidity, and pressure, harsh seismic activity levels, and dirty environments. Therefore, the development of these types of SOVs requires intricate technologies to meet the required performance specifications.

Most previous work on solenoid valve design has focused only on the static and dynamic behaviors of solenoid actuators, especially the coil and plunger, although the coil design is the core technology in a solenoid valve. There are not enough technical studies that describe the general design process for SOVs. Therefore, it is necessary to cover the entire range of the design process, including the design of the valve body, the materials, and the physical dimensions of the solenoid valve. Moreover, most domestic manufacturers of SOVs could not accomplish the development and localization of SOVs for special applications, and most of these high-valued valves are imported from foreign companies. This situation may be attributed to a lack of technology for the concept and/or basic designs in domestic companies, which have generally depended on a combination of reverse engineering and their experiences.

In this study, we have attempted to establish general processes for designing SOVs for special uses, such as in nuclear power plants, in the harshest environmental conditions. Special attention has been given to the DC 3-way normally closed valve to verify the suggested design methodology.

2 DESIGN PROCEDURE FOR SOV

The concept design process for SOVs is often disregarded by design engineers because most of the design concept is already well-known and is done by experiences based on reverse engineering or conventional models. However, this way of approaching the design is apt to miss important design factors, and it cannot be expected to produce a creative design or outcome. To remedy this common oversight, identification of all design constraints is the first and most important step of the design process. Generally, most of these constraints can be obtained from user requirements, various related technical codes/standards, and

Figure 1: Structure of direct-acting SOV
procurement specifications, including technical specifications.

The solenoid actuator has a similar design procedure except that its material is subjected to environmental conditions in the application, although there are various types of solenoid valves. In this work, we have divided the entire design process of the solenoid valve into five design steps relating to the solenoid actuator and the valve body. The order of the steps as explained in this chapter is the design process that we suggest for the solenoid valve. This order and some of the steps may generally be changed according to the design engineer, design logic, given input parameters, or design purpose. However, it is necessary to establish the general procedure for designing a SOV under given input parameters from the concept design and design specifications.

2.1 Attraction Force and Force Balance of the Plunger

The design concept and/or input parameters give information on the number of ports on the valve body, fail mode, type of closure, movement direction of the closure, and design pressure $P$. Then, as the first step of the SOV design, the orifice size $d$ of the valve body should be chosen based on the experience of the design engineer, which yields the fluid pressure force $F$ on the valve disc through the orifice by Eq. (1).

$$F = P \times \frac{\pi d^2}{4}$$

The fluid pressure force $F$ is a factor that determines the design attraction force $F_A$, as shown in Fig. 2, which shows the free-body diagram of the plunger in the SOV. In this work, we have designed a 3-port, 3-way, two spring closure type SOV. The cap spring force $F_c$ and plunger spring force $F_p$ can be calculated by the product of the displacements ($x_c, x_p$) and spring constants ($k_c, k_p$) for each spring. The spring displacements are obtained by combining the initial spring displacements and plunger strokes $x$. These initial displacements and spring constants are usually dependent on engineering experience from typical magnitudes of the attraction force of the solenoid. Then, the force balance for the moving plunger in Fig. 2 gives the minimum attraction force $F_{A,\text{min}}$ by Eq. (2).

$$F_{A,\text{min}} = F_p - F - F_c$$

The attraction force of the solenoid is an important design parameter that significantly affects the valve performances such as the response time and power consumption. The attraction force decreases with the degradation of the coil from aging and also with an increase of the coil temperature of the solenoid valve during operation. Therefore, the attraction force $F_A$ has a design margin by introducing the safety factor $s_f$ as shown in Eq. (3).

$$F_A = s_f \times F_{A,\text{min}}$$

It is worth noting that this design algorithm can also be used to calculate the orifice size $d$ of the valve body when the attraction force $F_A$ or $F_{A,\text{min}}$ is given. In addition to the orifice of the valve, the design of other parameters related to the dimension of the valve body can be found in [2], which explains how to determine the length, height, and width of the valve body based on simple geometry.

Fig. 2. Force balance for a plunger
2.2 Electric Resistance of Coil

The design process of SOV must determine the design parameters that have the maximum attraction force and good response characteristics at a given power consumption. Therefore, the design object value for the power consumption of the solenoid valve is given in many cases. Then, the rating current $I$ and resistance $R$ of the coil can be obtained from Eq. (4) and Ohm’s law Eq. (5) for a given consumption power $P_w$ and rating voltage $V$.

$$I = \frac{P_w}{V}$$  \hspace{1cm} (4)

$$R = \frac{V}{I}$$  \hspace{1cm} (5)

The current and resistance of the coil are key parameters in deciding the coil number of windings and, hence, the attraction force of the valve. In real SOV manufacturing, the coil resistance is a target value to be obtained by adjusting the total number of windings or the coil wire diameter.

2.3 Number of Coil Windings

The number of coil windings $N$ affects the design of the coil dimensions, the temperature increase inside the coil, and the attraction force. The relationship between the magnetomotive force $f$ and the magnetic flux density $B$ [T or Wb/m²] can yield the coil number of windings $N$, as shown in Eq. (6) [3]:

$$f = \frac{\zeta B(x + \delta)}{\mu_0} = NI$$

$$\therefore N = \frac{\zeta B(x + \delta)}{\mu_0 I}$$  \hspace{1cm} (6)

where $\delta$ is the anti-remanence gap, which is the space distance between the moving plunger and the stationary core; $\zeta$ is the equivalent coefficient (1.15 - 1.4); and $\mu_0$ is the magnetic permeability of air ($4\pi \times 10^{-7}$ H/m). The equivalent coefficient is introduced as a correction factor for the magnetomotive force required in the gap.

The flux density $B$ of an actual soft magnetic material experiences non-linearity and saturation on $B$-$H$ (flux density vs. field intensity) curves. The flux density $B$ of materials can be calculated by Eq. (7) [4], which can be obtained from the experimental results of the characteristic $B$-$H$ curve of the material [5]:

$$B = \frac{\Phi}{S} = \mu_0 H$$  \hspace{1cm} (7)

where $\Phi$ [Wb] is magnetic flux, and $S$ [mm²] is the effective cross-sectional area of the magnetic material. The flux density $B$ of the gap space can also be obtained from the semi-empirical relation in Eq. (8) [6]:

$$B = 0.4927(\log N_{idx} - 2)\nu$$  \hspace{1cm} (8)

where $\nu$ is the correction factor (0.8 - 0.9) for the $B$ definition, and $N_{idx}$ is the index number obtained from Eq. (9).

$$N_{idx} = \sqrt[\nu]{\frac{F_{A,min}}{x + \delta}}$$  \hspace{1cm} (9)
2.4 Plunger

The flux density $B$ can also yield the information about the plunger diameter $d_p$ through the relationship between the attraction force $F_A$ of the solenoid and the flux density $B$. The attraction force depends on the structural parameters of the solenoid valve, the exciting current of the coil, the permeability of various material components and plunger position [7] and can be expressed as Eq. (10) [3]:

$$F_A = \frac{1}{2} \frac{B^2 \cdot S_g}{\mu_0}$$  \hspace{1cm} (10)

where $S_g$ is the cross-sectional area of gap, Eq. (11). Then, the plunger diameter $d_p$ can be obtained by Eq. (12) if the diameter $d_p$ is assumed to be the same as the gap diameter.

$$S_g = \frac{\pi}{4} d_p^2$$  \hspace{1cm} (11)

$$d_p = \sqrt{\frac{8\mu_0 F_A}{\pi B^2}}$$  \hspace{1cm} (12)

2.5 Solenoid Coil

The design of the solenoid coil can start by considering the coil geometry as shown in Fig. 3. The inner radius of the coil, $r_i$, then can be obtain from Eq. (13), which is the same as the outer diameter of the bobbin, $d_b$:

$$r_i = \frac{d_p}{2} + t_b + d_s$$  \hspace{1cm} (13)

where $t_b$ is the thickness of the bobbin, and $d_s$ is the space distance from the plunger to the bobbin in Fig. 3.

When the ratio of height $h$ to width $W$ of the solenoid coil is fixed, the $h$ and $W$ of solenoid coil are obtained from the temperature rise $\theta_f$ relationship of the coil, as shown in Eq. (14):

$$\theta_f = \frac{q \rho \left( \frac{N \cdot I}{h} \right)^2}{2 \lambda \xi W}$$  \hspace{1cm} (14)

where $q$ is the duty ratio (1 for DC solenoid), $\rho$ is the resistivity of the coil wire ($1.68 \times 10^{-8} \ \Omega \cdot m$ for copper at 20 °C), $\lambda$ is the heat diffusion coefficient of the coil [W/m²°C], and $\xi$ is the space factor (0.65 - 0.8) of the coil. Resistivity is an intrinsic property of a material that is measured as its resistance to current per unit length for a uniform cross-section. The space factor is the ratio of the area of the coil wire conductor to the coil sectional area and is calculated by Eq. (15).

$$\xi = \frac{\pi}{4} \frac{d_w^2 \cdot N}{Wh}$$  \hspace{1cm} (15)

The width of the solenoid coil $W$, the number of winding layers $N$, and the number of turns per layer $n_c$ are all

---

Fig. 3. Coil geometry for SOVs
calculated by the geometry of the solenoid coil using Eq. (16), Eq. (17), and Eq. (18), respectively:

\[ W = (d_w + t_i) \times N_i \]  

(16)

\[ N_i = \frac{N}{n_c} \]  

(17)

\[ n_c = \frac{h}{d_w} \]  

(18)

where the diameter of the coil wire, \(d_w\), and the thickness of the interlayer insulation material, \(t_i\), are known. The diameter \(d_w\) can easily be selected from tables of AWG (American Wire Gauge) wire sizes, and interlayer insulation film may be used to reinforce the insulation performance because of its nuclear application. Substituting Eq. (16) through Eq. (18) into Eq. (14) gives the height of the solenoid coil, \(h\), as Eq. (19).

\[ h = \frac{qd \rho}{2 \lambda \xi \theta_f d_w (d_w + t_i)} \]  

(19)

All parameters in Eq. (19) are known values except \(d_w\) and \(\theta_f\). The \(\theta_f\) should be decided based on the design engineer’s experiences and some experimental data, design specifications, the insulation rating of the coil, and/or the ambient temperature. For a conservative design, we recommend \(\theta_f\) to be the maximum temperature difference between ambient temperature and the maximum temperature allowable for a given insulation class of the coil. Once the diameter \(d_w\) and \(\theta_f\) are fixed, the coil height \(h\), number of turns per layer \(n_c\), number of winding layers \(N_i\), and coil width \(W\) can be calculated using Eq. (19) to Eq. (16), respectively.

### 3 DESIGN VERIFICATION

In Chapter 2, all the design parameters for \(h\), \(n_c\), \(N_i\), \(W\), and \(r_o\) can be obtained after the selection of \(d_w\) from the AWG tables, which strongly depends on the engineer’s experience. However, the value of the \(d_w\) can be verified with the resultant design values obtained by the selection of \(d_w\) using Eq. (20).

\[ d_w = \sqrt{\frac{4 \rho (r_i + r_o)NI}{V}} \]  

(20)

Comparison of these \(d_w\) values to the values selected by the engineer validates the resistivity of the coil wire, \(\rho\), and the coil dimensions, such as \(r_i\), \(r_o\) and \(N\). The design engineer must again select \(d_w\) from the calculation of \(h\), \(n_c\), \(N_i\), \(W\), and \(r_o\) if the difference between \(d_w\) from Eq. (20) and the selected \(d_w\) is large.

The coil resistance \(R\) obtained from Eq. (5) in Chapter 2 can be confirmed with Eq. (21), which is a function of the coil resistance per unit length \(R_o\) [Ω/m] at a coil temperature of 20 °C and a total length of coil wire \(L\) [m]:

\[ R = R_o \times L \]  

(21)

where \(R_o\) can be obtained from the AWG tables for the selected \(d_w\), and \(L\) can be calculated from Eq. (22), which is based on the geometry of the solenoid coil:

\[ L = n_c N_i \pi \left\{ (N_i - 1)(d_w + t_i) + d_h \right\} + N_i \pi \left\{ 2N_i (d_w + t_i) + d_h \right\} \]  

(22)
where \( d_b \) is the diameter of the bobbin, which is assumed to be same as the inner diameter of the coil, \( 2r_i \), and \( N_r \) is the residual layer number of the coil, the residual of \( N/n_r \). The first term of the rightmost term in Eq. (22) is the coil length for the \( N_r \) layer, and the second is the coil residual length for the \( N_r+1 \) layer. This verification for the total coil resistance \( R \) is a chance to check the suitability of the design results for the \( r_i \), \( N_r \), and \( n_r \) of the solenoid coil to obtain the target value for the power consumption from Eq. (4).

The temperature inside the solenoid coil first increases with the operation time of the valve and is then saturated at a certain temperature. The increased temperature of the coil results in an increase of the resistance of the coil, which reduces the coil current and, hence, the attraction force of the solenoid valve. Therefore, it is worthwhile to compare the design attraction force \( F_A \) to the reduced attraction force \( F_{A,h} \) caused by the temperature increase \( \theta_f \). In this design program, the temperature rise is calculated using the difference between the maximum temperature representing the insulation rating of the coil and the ambient temperature \( T_a \). The increased resistance of the coil, \( R_h \), is shown in Eq. (23) as function of \( R_{20} \), which is the resistance of the coil at 20 \(^\circ\)C [8]:

\[
R_h = R_{20} \times \left( \frac{234.5 + T_h}{234.5 + 20} \right)
\]

(23)

where \( T_h [\^\circ\)C] is the saturated temperature of the coil, which is assumed to be the maximum temperature representing the insulation rating of the coil in this design program. This increased resistance \( R_h \) results in a reduced current \( I_h \) through Eq. (8). Then, the decreased flux density \( B_h \) and the reduced attraction force \( F_{A,h} \) are calculated using Eq. (24) and Eq. (10), respectively.

\[
B_h = \frac{\mu_0 I_h N}{\zeta(x + \delta)}
\]

(24)

This reduced attraction force \( F_{A,h} \) must be larger than the minimum attraction force \( F_{A,\min} \) to properly operate the valve, even at the elevated temperature \( T_h \). This comparison requires a design engineer to re-designate the safety factor \( s_f \), which affects the reduced attraction force \( F_{A,h} \) as well as the design attraction force \( F_A \). This corrected design attraction force \( F_A \) can yield the optimized design of the valve and can also re-designate the orifice size \( d \), which is the very starting point of the solenoid valve design process. Therefore, this verification logic can be regarded as a self-verified process covering the entire process of SOV design.

4 CONCLUSIONS

We have established a detailed procedure and a verification methodology for designing solenoid valves for use in nuclear power plants. As first step of the design, all of the design constraints should be defined based on user requirements, various technical codes/standards, and procurement specifications. Clear identification of these input parameters is an important step for the subsequent design process. Secondly, the general procedure of designing solenoid valve has been suggested based on our design experiences and physical/electromagnetic theories. The procedure includes many design parameters that are designated by design engineers based on their experiences, the input data, and physical relationships. Lastly, we have suggested a verification process for this design methodology, which increases the reliability of the design results suggested by this work and seems to be a powerful scheme for the reliable design of solenoid valves. This verification process includes calculations of the coil wire diameter \( d_w \), coil resistance \( R \), and reduced attraction force caused by the
temperature increase of the solenoid coil. Special attention has been paid to the reduced attraction force $F_{A,h}$, which must be larger than the minimum attraction force $F_{A,\min}$. The comparison of $F_{A,\min}$ to $F_{A,h}$ results in the optimal value of the safety factor $s_f$ that is used to determine the design attraction force $F_A$. The resulting tuned attraction force $F_A$ may decrease the required current through the coil, which creates an opportunity to decrease the power consumption of the valve. As a result, this verification logic allows the optimization of $F_A$, which is almost the starting point of the solenoid valve design process and thus results in the optimization of the design. Experimental data with the prototypes manufactured based on our design results show that the attraction force and coil current are in good agreement with the designed values.

This procedure may be useful in developing SOVs with new design specifications and also in simulating the effects of design parameters on performance. The proposed design method can enhance the reliability of the design, reduce the cost, and shorten the design and development time, and therefore has practical value for engineering purposes. Indeed, we have experienced significantly reductions in development time and cost when we have applied this template to the manufacturing of prototypes of new models of SOVs.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Research & Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy.

REFERENCES


