h' = height of bridge, Figure 4, m
H = magnetic field strength, A/m
I_c = capture current, A
I_r = release current, A
I_w = working current, A
$k_1, \ldots, k_{10}$ = constants
L = characteristic size of opening, m
L_g = grate spacing, m
L_s = screen aperture, m
$L_{s,max}$ = maximum aperture of screen beyond which particles cannot be stopped and held, m
L_{so} = size of screen opening at which bridging occurs naturally, m
r = distance away from a straight line conductor, m
t_{open}, t_{closed} = time period when the current to the MVS is off and on, respectively, s
W = weight of particles, N

Greek Letters

θ = angle between F_p and the horizontal
μ = magnetic permeability, H/m
μ_{eff} = effective permeability, H/m
μ_o = magnetic permeability in air or in a vacuum, H/m

LITERATURE CITED

Eisenstein, I., "Magnetic Separators: Traction Force between Ferromagnetic and Paramagnetic Spheres," *IEEE Trans. Magn.*, MAG-13, 1646 (1977).

Fink, D. G., and H. W. Beaty, *Standard Handbook for Electrical Engineers*, 11th Ed., 2, McGraw-Hill, New York (1978).

Harmens, A., "Flow of Granular Material through Horizontal Apertures," *Chem. Eng. Sci.*, 18, 297 (1963).

Resnick, W., Y. Heled, A. Klein, and E. Palm, "Effect of Differential Pressure on Flow of Granular Solids through Orifices," *Ind. Eng. Chem. Fund.*, 5, 392 (1966).

Wang, Y., E. Jaraiz M., O. Levenspiel, and T. J. Fitzgerald, "A Magnetic Control Valve for Flowing Solids (MVS): Exploratory Studies," *Ind. Eng. Chem. Process Des. Dev.*, 21, 717 (1982).

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Theory and Operational Characteristics of the Magnetic Valve for Solids

Part II: Collar Design

This paper reports on the operating characteristics of the collar type MVS which uses either orifice plates or screens as supports for the solids.

The optimum placement for the support (screens or orifice plates), the current needed to operate the valve as a function of vessel size (up to 0.55 m) and screen or orifice opening, and the response characteristics of the valve were all determined. These findings were then compared with theory.

Finally, the operational characteristics of the MVS (magnetic valve for solids) when handling a mixture of magnetic and nonmagnetic solids were briefly examined.

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SCOPE

This paper as well as Part I explore the characteristics of a new class of valve to control the flow of solids in pipes and vessels. They operate by properly developing a strong magnetic field in a narrow slice of flow channel. These valves have no mechanical action and are very rapid acting, however they do require the presence of at least some small fraction of magnetic material in mixture of solids.

There are numerous possible designs for these devices. In contrast with the grate design, this paper deals with the design in which the electrical conductor does not protrude into the flow channel for solids but is coiled around it. Each design has its particular characteristics and advantages.

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CONCLUSIONS AND SIGNIFICANCE

1. Measurements of magnetic flux densities (Figures 4–7) suggested that the supporting screen or orifice plate should be located level with or slightly above the bottom of the conducting coil (Figure 8) which itself should be encased in a soft iron shield.

2. Experiments with orifice plates showed that the operating current needed was proportional to $d_{or}^{1/2}$ beyond the critical bridging diameter of orifice (Figure 10), that this current was highest for the orifice located at the axis of the flow tube, but that the mass flux of solids when the valve was open was independent of orifice location (Figure 11) or the number of holes in the orifice plate.

3. Experiments with screens showed that the current needed to operate the valve was directly proportional to cross-sectional area of flow channel (Figure 15), proportional to the square root of the screen aperture beyond a critical bridging aperture (Figure 12), and that it decreases slightly with increase in particle diameter (Figure 16). This dependency on vessel size did not match the predictions of theory.

4. Experiments with mixtures of magnetic and nonmagnetic solids showed that the MVS operated satisfactorily with as little as 10% of magnetic solids (Figure 17), but that the current needed increased more and more sharply as the fraction of magnetic material was reduced to zero (Figure 18).

5. This study shows that the collar type MVS can operate satisfactorily as an on-off valve, has a extremely rapid response and can control the flow rate at any desired value.

6. The advantage of this device over the grate-type MVS (see Part I) is simplicity in construction because the electrical conductors are not inserted into the flow channel. However, it needs more power to operate than does the grate design.

INTRODUCTION

By properly generating a strong magnetic field in a rather narrow slice of flow channel the flow of a stream of solids containing magnetic material can be controlled or stopped, effectively and rapidly, all with no moving parts or mechanical action. Devices for doing this are called magnetic valves for solids, MVS. There are three broad classes of MVS: the grate, the collar and the external coil designs. Part I of this paper illustrates these, and the operational characteristics of one of these designs, the grate.

This paper reports on the collar-type MVS. Here the electric conductor is coiled around the outside of the flow channel, while a screen, perforated plate or other partial obstruction is located within the flow channel.

When the valve is closed (current turned on) and the flow channel free of solids the magnetic flux lines are as shown in Figure 1a. With magnetic particles flowing through the channel, the particles line up in chains along the magnetic flux lines, are hindered by the screen, form clusters and build up on the screen, bridge from wire to wire, eventually blocking the flow channel. The screen or partial obstruction is essential to the operation of the MVS because it provides the initial support for the particles.

With the valve closed and the particles held up by the screen, the magnetic flux lines are guided through the solids and are amplified because of the higher density of magnetic material there. They also turn rather sharply close to the screen because of the abrupt change in magnetic permeability at the screen. The screen can be nonmagnetic, or better still, of magnetic material, because the latter distorts and collects the magnetic flux lines. Finally, a soft iron shield surrounding the coil serves to guide and even further amplify the magnetic flux, thus increasing the efficiency of the MVS by allowing it to operate at lower power levels. The flux lines for the valve when it is holding up solids is shown in Figure 1b.

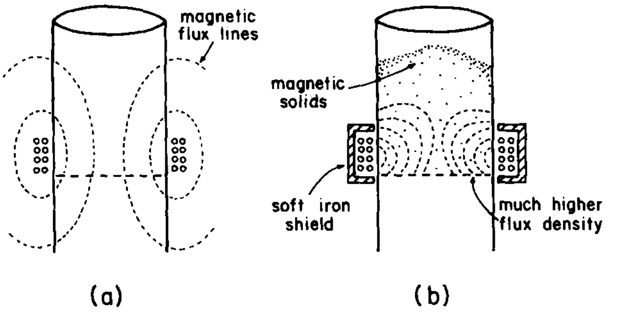

Figure 1. (a) Magnetic flux lines at the MVS with an empty tube. (b) With a packed bed and soft iron shield one has a much higher flux density.

The current needed to stop the flow of solids we call the capture current I_c, and the current below which the particles can no longer be held we call the release current I_r. Because falling particles have kinetic energy and maintain a lower magnetic flux density (larger void fraction), the capture current is always greater than the release curent. The working current for the valve I_w is chosen a bit higher than the capture current, thus

$$I_w > I_c > I_r$$

This paper presents the predictions of theory which relate the release current to diameter of flow channel, height of conducting coil, placement of screen relative to the coil, and aperture of screen.

The first set of experiments measures the magnetic flux density for various geometries. This suggests the optimum placement of the screen with respect to the coil. Then the release current is measured in various flow channels from 84 to 554 mm in diameter for various geometries of screen and coil, using both pure magnetic particles and mixtures of magnetic and nonmagnetic particles (up to 90% nonmagnetic). The results of these experiments are then compared with the predictions of theory.

THEORY

A collar-type MVS just keeps a suspended packed bed of solids from flowing when the frictional drag between particles ready to slide through an aperture of the screen past those being supported by the screen just equals the weight of the suspended particles, or when

$$F_f = F_g \tag{1}$$

This situation is shown in Figure 2. In the above expression the weight of the particles ready to slide through the aperture is given by

$$F_g = (1 - \epsilon)\,\rho_p L_s^2 h' \tag{2}$$

while the frictional resistance F_f is given by

$$F_f = k_1 \begin{pmatrix}\text{number of facing}\\ \text{pairs of particles}\end{pmatrix} \begin{pmatrix}\text{horizontal force}\\ \text{between facing particles}\end{pmatrix} = k_1 \left(\frac{4L_s h'}{d_p^2}\right) F_h \tag{3}$$

Now the force on a magnetic particle in a magnetic field has two components, namely the particle-to-particle attraction along the

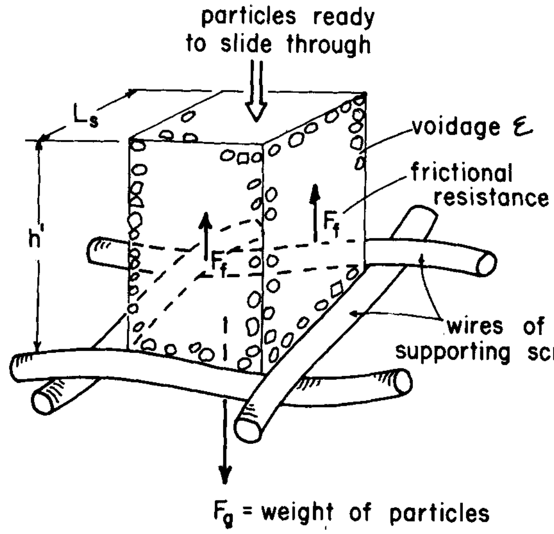

Figure 2. Forces on particles ready to slide through a screen aperture.

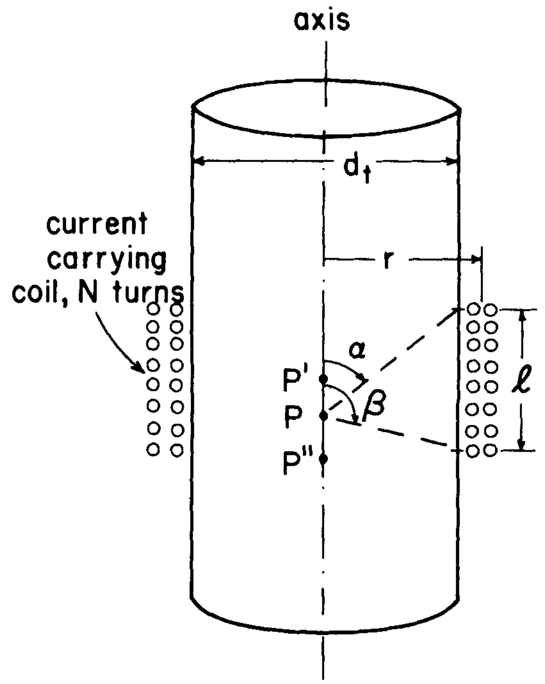

Figure 3. Sketch to show the variables which affect the magnetic flux density at the axis of a solenoid.

magnetic flux line, and the particle-to-conductor attraction normal to the magnetic flux line. Part I showed that the horizontal component of this force is given by

$$F_h = k_2 d_p^2 M^2 \tag{4}$$

where M is the magnetization of the particles, given by

$$M = \frac{B}{\mu_0} - H = \frac{\mu_{\text{eff}} H}{\mu_0} - H = \left(\frac{\mu_{\text{eff}}}{\mu_0} - 1\right) H \tag{5}$$

and where k_2 depends on the nature of the medium and the angle of inclination of the magnetic flux lines to the horizontal.

Next evaluate the magnetic field intensity H within the MVS of Figure 1. Since the magnetic field intensity may be expected to be weakest at the axis of the flow channel consider the release current only at this location. Referring to Figure 3, electromagnetic theory (Winch, 1963) gives the magnetic field intensity at any point P along the axis of an electrical coil, or solenoid, as

$$H = \frac{NI_r(\cos\alpha - \cos\beta)}{2l} \tag{6}$$

At the midpoint of the solenoid P' Eq. 6 becomes

$$H = \frac{NI_r}{\sqrt{4r^2 + l^2}} \tag{7}$$

while level with the end of the solenoid P'' Eq. 6 becomes

$$H = \frac{NI_r}{\sqrt{4r^2 + 4l^2}} \tag{8}$$

So with the screen level with the lower end of the coil, and for the screen aperture located at the axis of the flow channel (weakest force here), and for the situation where a bed of magnetic particles is resting on the screen, Eqs. 5 and 8 combined give the magnetization of particles M as

$$M = \left(\frac{\mu_{\text{eff}}}{\mu_0} - 1\right) \frac{NI_r}{\sqrt{4r^2 + 4l^2}} = \bar{\mu} \frac{NI_r}{\sqrt{4r^2 + 4l^2}} \tag{9}$$

where $\bar{\mu}$ is a mean permeability along the whole magnetic flux line, which accounts for the nonhomogeneity of the medium including air gaps at the walls, between particles, and so on. Replacing Eq. 9 in Eq. 4, Eq. 4 in Eq. 3, Eqs. 3 and 2 in Eq. 1 then gives, on rearranging,

$$NI_r = \frac{k_3(1-\epsilon)^{1/2}\rho_p^{1/2}\sqrt{r^2 + l^2}\, L_s^{1/2}}{\bar{\mu}} \tag{10}$$

Now at low magnetic flux density $\bar{\mu}$ is constant, meaning that one is nowhere near saturation for the material. In this case Eq. 10 shows that

$$NI_r \propto \sqrt{r^2 + l^2}\, L_s^{1/2} \tag{11}^*$$

For a narrow coil ($l \ll r$) this expression shows that the number of ampere-turns needed to hold the particles in place is proportional to the diameter of the flow channel and to the square root of the screen aperture.

On the other hand when saturation is reached M remains constant and independent of H. Thus

$$\bar{\mu} \propto \frac{1}{H} \tag{12}$$

Replacing Eqs. 12 and 8 in Eq. 10 leads to the conclusion that

$$L_s = L_{s,\max} = \text{constant} \tag{13}^*$$

at any value of $r^2 + l^2$. This means that there exists a maximum screen opening beyond which particles cannot be stopped and held. This maximum is reached at saturation of the magnetic medium.

These two expressions, Eqs. 11 and 13, represent the two extremes in possible behavior, and will be compared with experiment.

If a perforated plate is used in place of the screen the analysis is similar but with orifice opening d_{or} replacing screen aperture L_s. Thus at low flux density Eq. 11 is modified to give

$$NI_r \propto \sqrt{r^2 + l^2}\, d_{or}^{1/2} \tag{14}^*$$

while at high flux density, Eqs. 13 becomes

$$d_{or} = \text{constant} \tag{15}^*$$

One would expect an iron screen to distort and amplify the magnetic flux density somewhat, thus reducing the current needed to operate the MVS, however we would not expect the dependency on the various geometric factors as given by Eqs. 11 and 13 to change.

EXPERIMENTAL PROCEDURE AND MATERIAL

The equipment consisted of an adjustable D.C. power supply, a digital ammeter, plastic flow pipes of various sizes, solenoids made of copper tubing, copper and iron screens, perforated iron and plastic plates. The

TABLE 1. RANGE OF OPERATING CONDITIONS

Type	Iron Wire Screen 1	2	3	4*	5*
d_s, mm	0.7	0.8	1.0	1.2	1.6
L_s, mm	6.4	8.5	12.0	6.4	12.8

Particles

Type of Particles	d_p, mm	ρ_p, kg/m^3
Porous Iron	0.24	1390**
Solid Iron	1.41, 1.00, 0.53	7800
Sand	0.28	1270**

Tubes and Pipes

Type	Inside Diameter, mm
Plastic Pipe for Flow Channel	84
	146
	300
	554
Copper Tube for Coiled Conductor	4.8
Polypropylene Insulating Sheath	6.35

* Also made from copper.
** ρ_p = bulk density of particles.

coiled copper tubes were kept insulated from each other by heat-shrunk polypropylene tubing and were kept cool and isothermal by flowing water through them. Because the holding power of a MVS is only dependent on the current and is independent of the voltage we selected 5 V power supplies for reasons of safety.

Table 1 shows the range of operating conditions explored in this study.

PRELIMINARY EXPERIMENTS

Magnetic Flux Density in the Vicinity of the Collar-Type MVS

Figures 4–7 map the magnetic flux density as measured by a Hall effect generator in the vicinity of the MVS for various geometries. In order to compare the results all measurements were made at the fixed operating conditions shown in Table 2. Consider these figures in turn.

Figure 4 shows the measured magnetic flux density for a copper coil and pipe alone—no screen, no solids in flow or frozen in place, and no shield around the coil. At the midpoint P', and level with the end of the coil P'', we find by experiment

$$B\ (\text{at } P') = 7.5 \times 10^{-3}\ \text{Wb/m}^2 \tag{16}$$

$$B\ (\text{at } P'') = 7.1 \times 10^{-3}\ \text{Wb/m}^2 \tag{17}$$

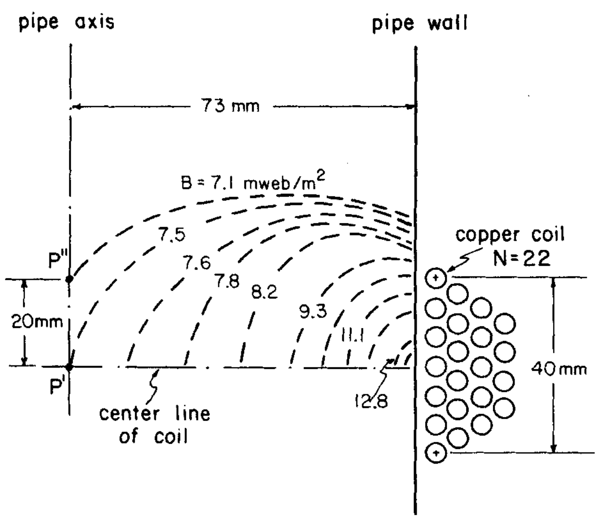

Figure 4. Distribution of magnetic flux density in the flow pipe without shield and screen.

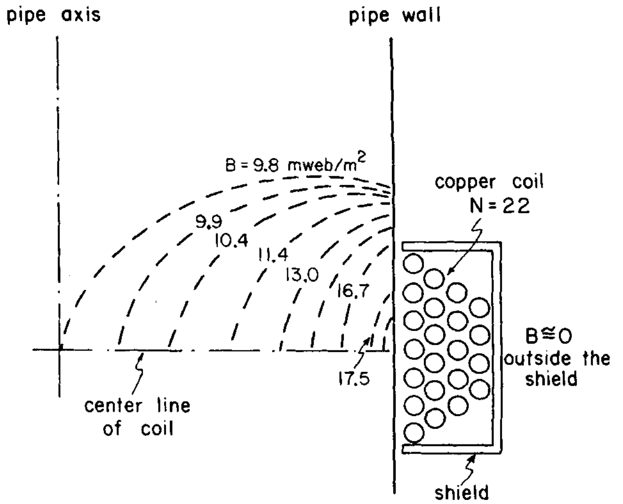

Figure 5. Magnetic flux density in the flow pipe with shield but without screen; d_t = 146 mm.

Let us compare these measured values with theory. First, B and H are related by

$$B = \mu_o H \tag{18}$$

where μ_o for the medium is that of free space, or

$$\mu_o = 4\pi \times 10^7\ \text{Wb/A} \cdot \text{m} \tag{19}$$

Combining Eqs. 7, 18 and 19 and using values for the geometry of the system used, Table 2, gives

$$B(\text{at } P') = \frac{(4\pi \times 10^{-7})(22)(40)}{[4(0.084)^2 + (0.034)^2]^{1/2}} = 6.45 \times 10^{-3}\ \text{Wb/m}^2 \tag{20}$$

Similarly Eqs. 8, 18 and 19 combined give

$$B(\text{at } P'') = 6.10 \times 10^{-3}\ \text{Wb/m}^2 \tag{21}$$

The calculated values from Eqs. 20 and 21 are not too different from the experimental values given by Eqs. 16 and 17.

Figure 5 shows that when a soft iron shield surrounds the solenoid the magnetic flux density in the flow pipe is enhanced, while outside the shield it is close to zero. This means that there is very little flux leakage outside the shield and that the shield provides a good guide for the magnetic flux lines.

It was found that the presence of an iron screen level with the center of the solenoid does not change the magnetic flux density much. However

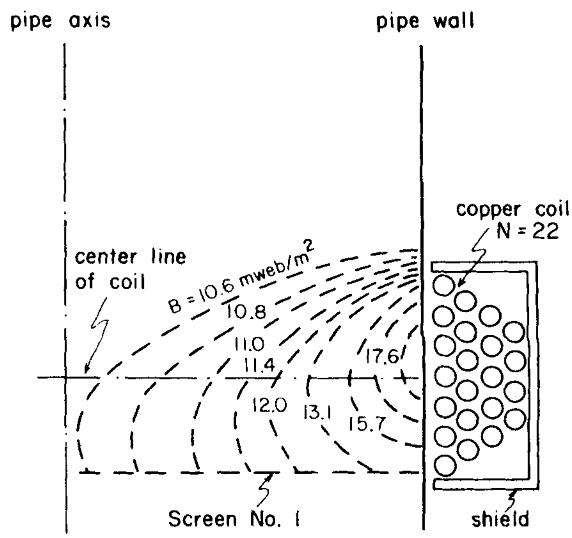

Figure 6. Magnetic flux density in the flow pipe with shield and with iron screen placed level with the bottom of the copper coil; d_t = 146 mm.

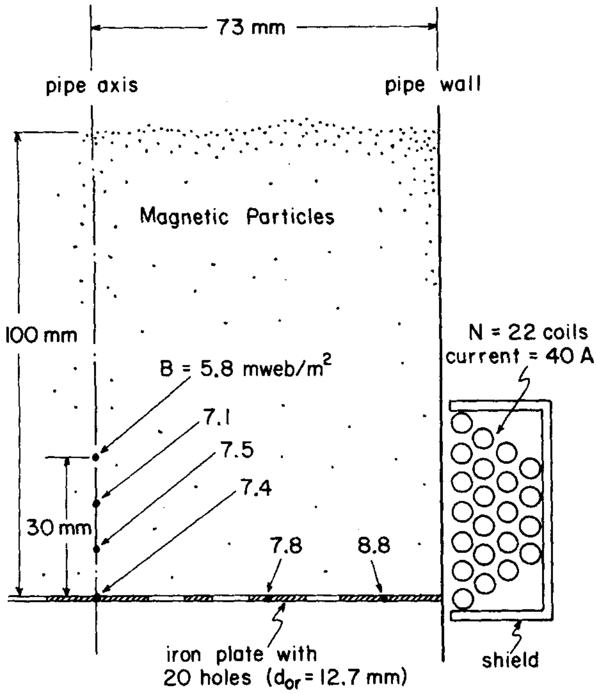

Figure 7. Magnetic flux density in the flow pipe holding up a bed of porous iron particles.

if the screen is located level with the bottom of the solenoid, as shown in Figure 6, the magnetic flux density at the solenoid is more uniform at the screen and is higher at the axis of the flow pipe than at any other location. Because of this all further runs were made with the iron screen located level with the bottom of the solenoid, and with an iron shield enveloping the solenoid.

When a bed of iron particles is held on the screen the magnetic flux density above the bed is more uniform than in an empty bed. Within the bed the axial and radial flux density is as shown in Figure 7. Also, the flux density is higher for shallow beds than for deep beds.

These experimental results give a picture of the distribution of the magnetic flux density associated with a collar-type MVS.

Placement of Iron Screen on Release Current of the MVS

Figure 8 represents experiments using porous iron particles and iron screen No. 1 in the 146 mm flow pipe. It shows the importance of placing

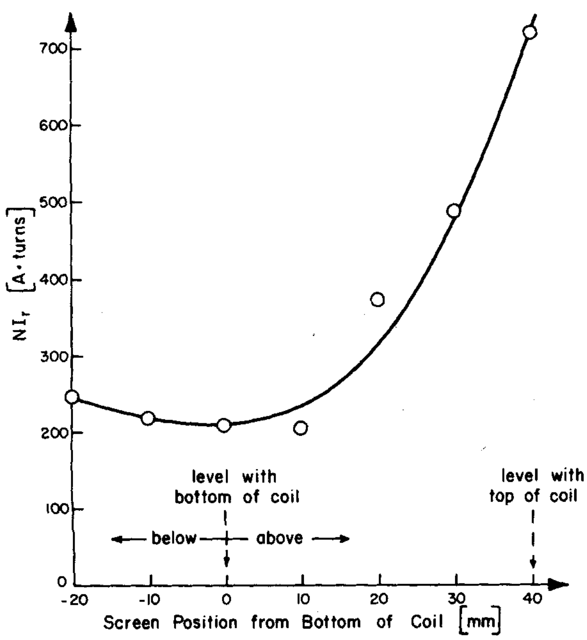

Figure 8. The release current is dependent on the placement of the iron screen; d_t = 146 mm, screen No. 1.

TABLE 2. OPERATING CONDITIONS USED IN MAPPING THE MAGNETIC FLUX DENSITY IN THE VICINITY OF A MVS

Working Current, I_w	40 A
Diameter of Flow Pipe, d_t	146 mm (~6 in.)
Turns of Copper Coil, N	22
Mean Length of the Four Layer Solenoid, l	34 mm
Distance from Axis of Pipe to Center of Solenoid, r	84 mm
Thickness of Soft Iron Shield Surrounding Solenoid	2 mm

the screen level with the bottom of the solenoid or a short distance above, and it verifies the findings of Figure 6.

Effect of Bed Depth on Mass Flux of Solids Through the MVS

Figure 9 shows that the mass flux of porous iron particles for two different valve opening times, t_{open}, is independent of bed depth as long as the depth exceeds some minimum value. The reason for this finding is that most of the weight of the particles is supported by the bridging of particles supported by the screens and by the walls of the pipe. This result agrees with studies by Altenkirch and Eichhorn (1981).

To eliminate bed depth effects all further runs were made at depths well in excess of the critical depth of about 150 mm.

EXPERIMENTS WITH ORIFICE PLATES

Release Current in Plates With One Hole

Experiments were conducted to determine the capture and release currents of iron and plastic plates, each containing a single centrally located orifice. Equation 14 suggests that a plot of NI_r versus $d_{or}^{1/2}$ should give a straight line passing through the origin. On the contrary the plot of Figure 10 does not extrapolate to the origin but to a zero flow when the orifice size is reduced to about 8 particle diameters.

Studies on flow of granular material through horizontal apertures (Harmens, 1963) show that when $d_{or} \cong 6\,d_p$ the flow of particles from an orifice becomes erratic while at $d_{or} \leq 4\,d_p$ flow is likely to stop due to the bridging of particles. This bridging phenomenon is the most reasonable explanation for the deviation of experiment from theory. Naturally, the bridging diameter depends on the nature and shape of the particles. The particle "stickiness" resulting from their mutual attraction in the magnetic field may explain the larger critical value of 8 d_p instead of about 4 d_p. Also, note that orifices in iron plates require lower currents than do orifices in plastic plates, most likely because these plates amplify and guide the magnetic flux.

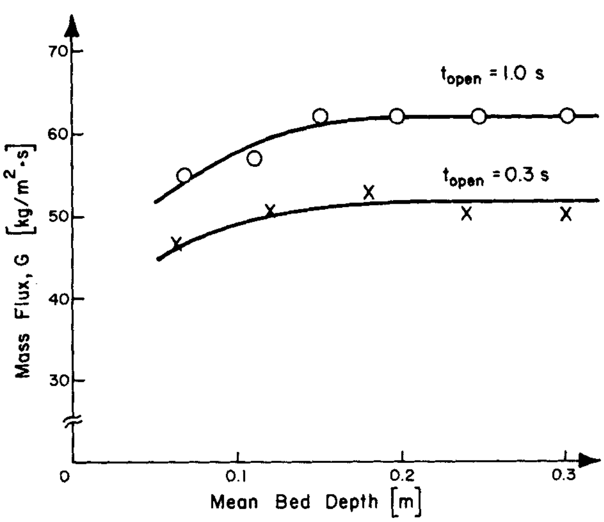

Figure 9. Except for very shallow beds the mass flux of solids is independent of bed height; d_t = 146 mm, I_w = 16 A, N = 22 turns.

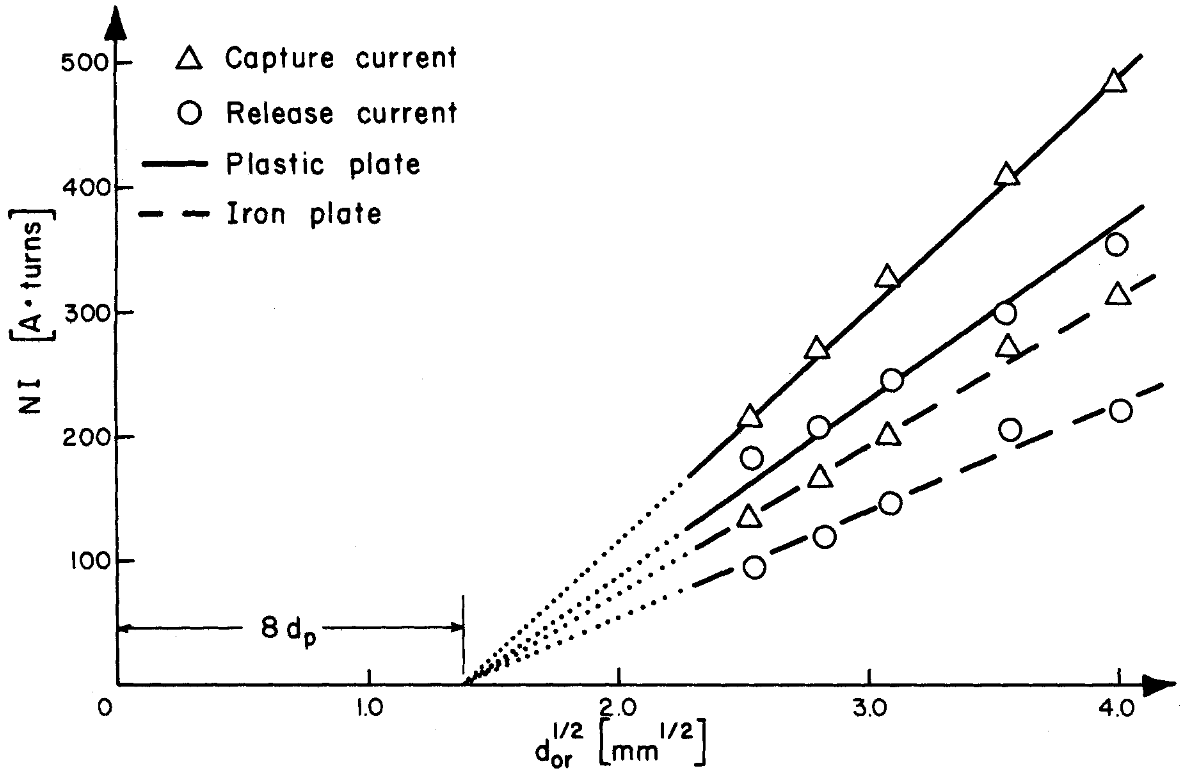

Figure 10. The relationship between the current and orifice size in iron and plastic plates, d_t = 146 mm, N = 22 turns.

Current and Mass Flux Through an Orifice Plate

Figure 11 shows that the placement of the orifice in the iron plate affects both the capture and release currents but not the mass flux of particles through the orifice. It is apparent that a centrally located orifice requires the highest current. This fact is explained by noting that the magnetic flux density is lowest at the center of the flow tube, as shown in Figures 6 and 7.

Experiments with iron plates containing 1, 5, 10, 15, 20 and 25 orifices verify that the mass flux, based on the open hole area, is constant.

EXPERIMENTS WITH SCREENS

Release Current for Different Iron Screens

Figure 12 shows the effect of different apertures of iron screens on the release current. Clearly, the release current becomes smaller as the aperture of the screen is reduced, with bridging at about 22 particle diameters.

Figure 13 expresses the influence of different apertures of iron screen on the mass flux of porous iron particles and shows that the mass flux becomes smaller as the aperture is reduced, with bridging occurring at about 15 particle diameters.

The difference in extrapolated values, 15 d_p and 22 d_p, is puzzling.

Mass Flux of Porous Iron Particles for Different Screen Apertures

Figure 14 expresses the influence of different apertures of iron screen on the mass flux of iron particles. It can be seen that the mass flux increases with screen aperture, in all cases becoming constant when t_{open} is longer than 1 s. This constancy beyond 1 s means that the response of the valve to switching is very much smaller than 1 s.

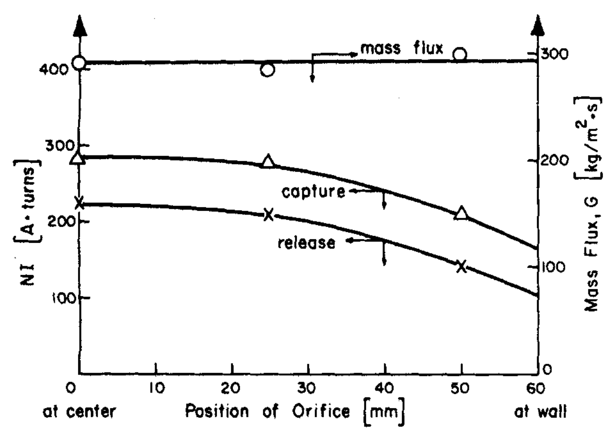

Figure 11. The location of the orifice in an iron plate does not affect the mass flux of solids but it does affect the current needed to operate the MVS; d_t = 146 mm, d_{or} = 12.7 mm.

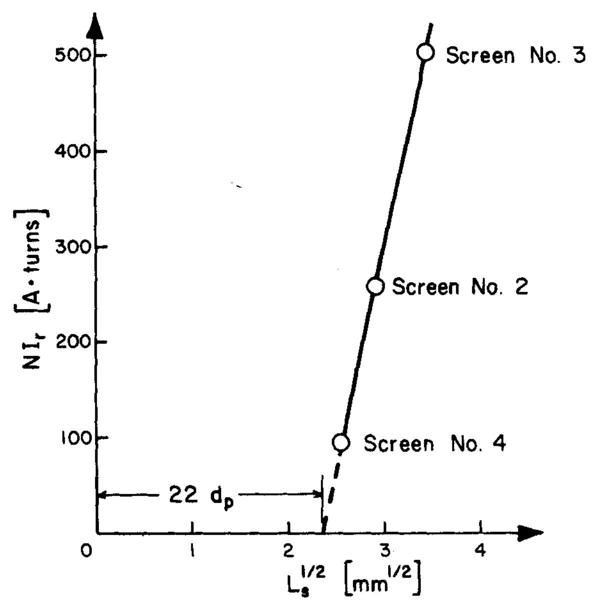

Figure 12. The effect of different iron screen apertures on the release current; d_t = 146 mm, N = 22 turns and porous iron particles.

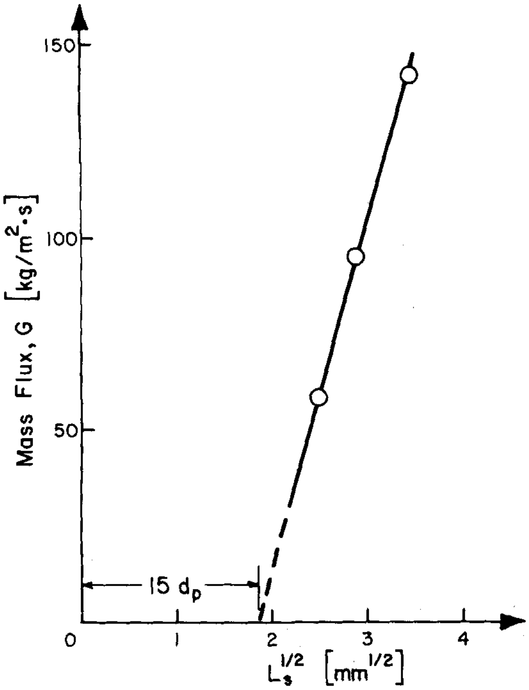

Figure 13. The relationship between the mass flux of porous iron particles and screen aperture; d_t = 146 mm, N = 22 turns.

Effect of a Collar Surrounding the Coil and of Type of Screen on the Performance of a MVS

Experiments using screen No. 4, porous iron particles (d_p = 0.24 mm), and 6, 12, and 22 turns of copper tube around a 146 mm flow tube show that

Without shield, $NI_r \cong 191$ A-turns

With shield, $NI_r \cong 105$ A-turns

The shield clearly improves the effectiveness of the MVS by guiding and amplifying the magnetic flux density of the valve.

Table 3, summarizing data taken with No. 4 and No. 5 copper and iron screens in a 146 mm flow pipe, shows that the iron screen requires about 1/3 to 1/4 of the current needed when using the copper screen. The action is similar to that of the shield around the coil in that the magnetic flux is amplified with an iron screen, but not with a copper screen.

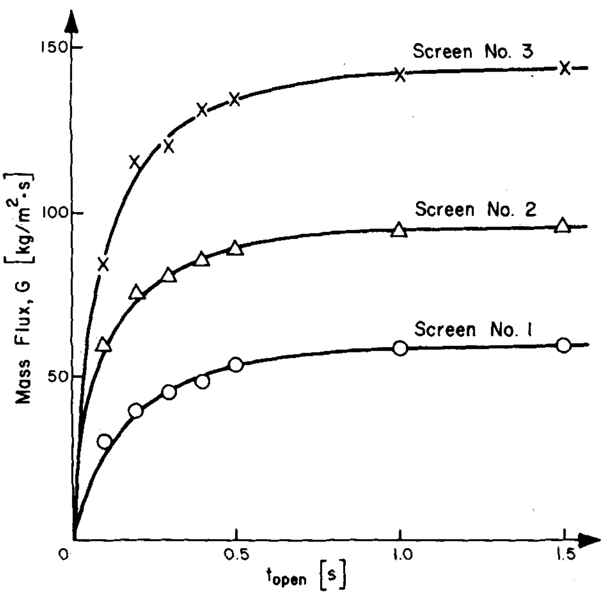

Figure 14. The effect of different screen apertures and valve-open times on the mass flux of porous iron particles; d_t = 146 mm, N = 22 turns.

Table 3. Influence of Different Screen Material

Type of Screen	Iron No. 4	Iron No. 5	Copper No. 4	Copper No. 5
NI_r, A·turns	88	246	422	805
NI_c, A·turns	136	328	528	909

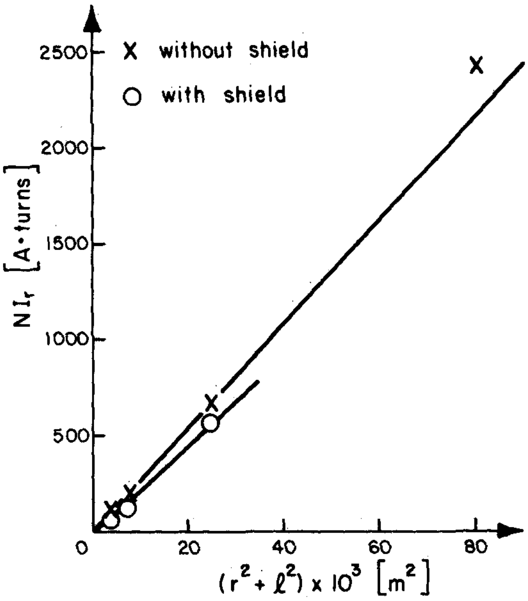

Figure 15. The effect of different diameters of flow pipe on release current; N = 12 turns, iron screen No. 4.

Release Current for Different Sized Flow Tubes

Theory which leads to either Eq. 11 or 13 predicts that the release current should be either directly proportional to the vessel diameter or else independent of vessel diameter. Neither prediction was supported by experiment. In fact, as shown in Figure 15, the release current seemed to be proportional to the area of flow tube. Further examination of this disagreement is needed.

Release Current for Particles of Different Size

Figure 16 confirms the preliminary findings on a different type of MVS (Wang et al., 1982) that the release current for screens decreases slightly with increase in solid iron particle size. Possible reasons for this are that

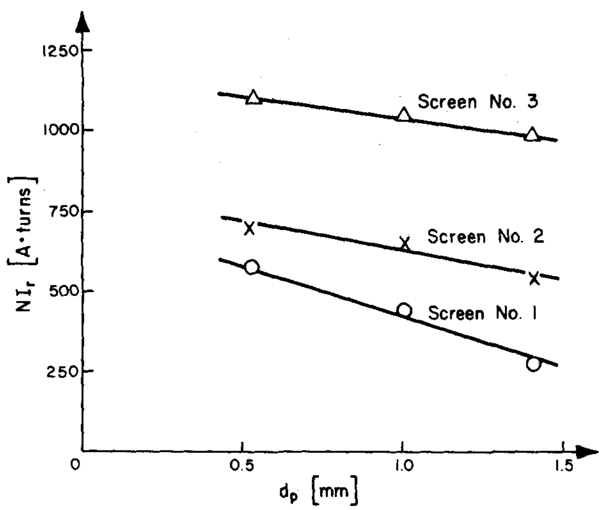

Figure 16. The release current increases somewhat with smaller particles irrespective of screen aperture; d_t = 146 mm, N = 22 turns and solid iron particles.

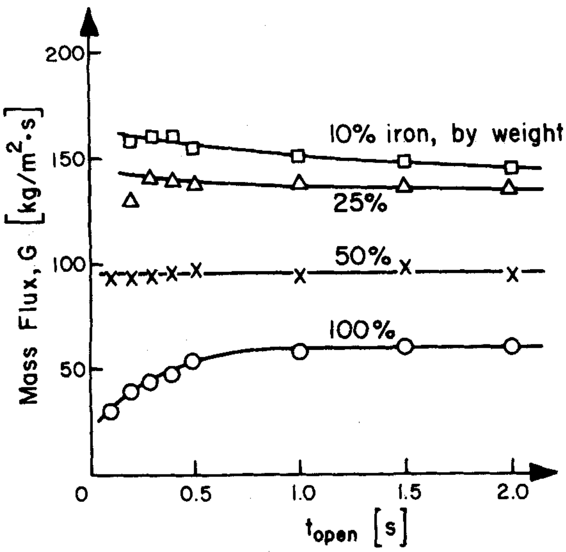

Figure 17. Nonmagnetic particles (relatively smooth sand) flow faster than magnetic particles (jagged porous iron); d_t = 146 mm, N = 22 turns, screen No. 1.

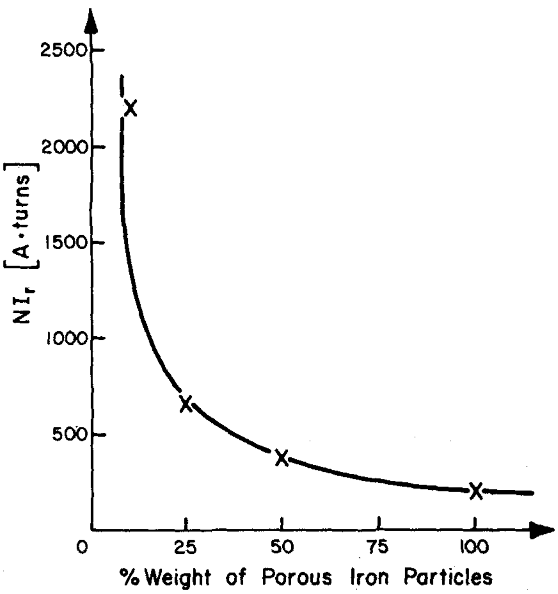

Figure 18. Lowering the amount of magnetic solids in the mixture increases the currents needed to operate the MVS; d_t = 146 mm, N = 22 turns, screen No. 1.

bridging plays a larger role for larger particles held up on a given screen, and because the frictional resistance to the sliding of particles past each other is greater for larger particles.

EXPERIMENTS WITH MIXTURES OF MAGNETIC AND NONMAGNETIC PARTICLES

Mass Flux of Various Mixture Ratios

For an iron screen No. 1 Figure 17 shows that the mass flux of mixed particles (porous iron particles and sand) increases as the fraction of nonmagnetic material increases. This difference in mass flux can be attributed to the different fluidity resulting from the two types of particles, the porous iron being very jagged and spongelike while the sand is relatively smooth. In any case the mass flux becomes constant for $t_{open} > 1$ s indicating that the acceleration and deceleration times are very much smaller than 1 s.

Release Current for Various Mixture Ratios

Figure 18 shows that the current needed to operate the MVS increases extremely rapidly as the fraction of magnetic solids in the mixture approaches zero.

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NOTATION

B	= magnetic flux density, Wb/m^2
d_{or}	= diameter of an orifice, m
d_p	= mean diameter of particles, m
d_t	= inside diameter of flow pipe, m
d_s	= diameter of screen wire, m
F_f	= frictional force, N
F_g	= force of gravity, N
F_h	= horizontal force between facing particles, N
G	= mass flux of particles, kg/m^2 (open area)·s
h'	= effective bridging height, Figure 2, m
H	= magnetic field intensity, A/m
I	= current flowing through the copper tube conductor, A
I_r	= release current, A
I_c	= capture current, A
I_w	= working current, A
k_1,k_2,k_3	= constants
l	= height of copper coil, m
L_s	= aperture of screen, m
$L_{s,max}$	= maximum aperture of screen beyond which particles cannot be stopped and held, m
N	= number of turns of copper coil
r	= radius of copper coil, m
t_{open}	= time period when the valve is opened (current turned off), s

Greek Letters

$\bar{\mu}$	= mean permeability along the whole magnetic flux line, Wb/A·m
μ_{eff}	= effective permeability, Wb/A·m
μ_o	= magnetic permeability of air or in a vacuum, Wb/A·m should be same as in part 1
ρ_p	= density of particles, kg/m^3
ϵ	= voidage of a packed bed of solids

LITERATURE CITED

Altenkirch, R. A., and R. Eichhorn, "Effect of Fluid Drag on Low Reynolds Number Discharge of Solids from a Circular Orifice," *AIChE J.*, **27**, 593 (1981).

Harmens, A., "Flow of Granular Material Through Horizontal Apertures," *Chem. Eng. Sci.*, **18**, 297 (1963).

Wang Y., E. Jaraiz-M., O. Levenspiel, and T. J. Fitzgerald, "A Magnetic Control Valve for Flowing Solids (MVS): Exploratory Studies," *Ind. Eng. Chem. Process Des. Dev.*, **21**, 717 (1982).

Winch, R. P., *Electricity and Magnetism*, 2nd Ed., 380, Prentice-Hall, Englewood Cliffs, NJ (1963).

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