Effect of Drag-Reducing Agent on Slug Characteristics in Multiphase Flow in Inclined Pipes

C. Kang

W. P. Jepson

M. Gopal

NSF I/UCRC, Corrosion in Multiphase Systems Center,
Department of Chemical Engineering,
340½ West State Street,
Athens, OH 45701

The effect of drag-reducing agent (DRA) on multiphase flow in upward and downward inclined pipes has been studied. The effect of DRA on pressure drop and slug characteristics such as slug translational velocity, the height of the liquid film, slug frequency, and Froude number have been determined. Experiments were performed in 10-cm i.d., 18-m long plexiglass pipes at inclinations of 2 and 15 deg for 50 percent oil-50 percent water-gas. The DRA effect was examined for concentrations ranging from 0 to 50 ppm. Studies were done for superficial liquid velocities between 0.5 and 3 m/s and superficial gas velocities between 2 and 10 m/s. The results indicate that the DRA was effective in reducing the pressure drop for both upflow and downflow in inclined pipes. Pressure gradient reduction of up to 92 percent for stratified flow with a concentration of 50 ppm DRA was achieved in 2 deg downward inclined flow. The effectiveness of DRA for slug flow was 67 percent at a superficial liquid velocity of 0.5 m/s and superficial gas velocity of 2 m/s in 15 deg upward inclined pipes. Slug translational velocity does not change with DRA concentrations. The slug frequency decreases from 68 to 54 slugs/min at superficial liquid velocity of 1 m/s and superficial gas velocity of 4 m/s in 15 deg upward inclined pipes as the concentration of 50 ppm was added. The height of the liquid film decreased with the addition of DRA, which leads to an increase in Froude number.

Introduction

It is well known that the addition of a small amount of drag-reducing agent (DRA) can reduce the pressure drop in pipeline. Numerous studies of drag reduction have been performed for about 50 yr. The simultaneous flow of multiphase (oil/gas and oil/water/gas) mixtures is a common occurrence in oil and gas pipelines. The pressure drop in these pipelines can be a very significant problem since many oil wells are located in remote sites. However, there is a conspicuous absence of drag reduction work for these multiphase flow pipelines. There are a number of advantages to DRA use in multiphase pipeline. These benefits of DRA include the reduction of operation costs such as pumping power and shutdown of pump station, increased production, and reduction in corrosion rate.

Reddy (1986) examined the effect of the pressure drop for single-phase flow using several drag-reducing agents in 2.5-cm pipeline. He reported that maximum drag reduction of 40 percent using Xanthangum was obtained in the recirculatory flow at 16 gpm flow rate.

Rosehart et al. (1972) have shown the effect of DRA in single and two-phase flow in 2.5-cm-dia horizontal pipes. They indicated that slug translational velocity was unchanged with the presence of polymer by visual observation. However, no measurements were made. They also reported that the slug frequency at low polymer concentrations was the same as for the air/water system, while the slug frequency at higher polymer concentrations decreased.

The effect of DRA in 10-cm i.d. system for single and three-phase oil/water/gas flow has been studied by Kang et al. (1998). They reported that DRA was effective in reducing the pressure gradients in different flow patterns such as full pipe flow, stratified flow, slug flow, and annular flow. They also showed that the flow pattern was changed in horizontal pipes as DRA was added.

Jepson and Kouba (1989) have shown that there are different types of slugs. They also reported that the strength of the slug is proportional to the Froude number calculated in the liquid film ahead of the slug. The equation is as follows:

$$Fr = \frac{V_t - V_{LF}}{\sqrt{g h_{eff}}}$$

Kang et al. (1998) have studied the effect of DRA on corrosion and slug characteristics in multiphase flow pipeline. They have shown that slug translational velocity does not change with DRA concentrations.

Effectiveness of DRA can be defined as follows:

$$\text{Effectiveness} = \frac{\Delta P_{\text{without DRA}} - \Delta P_{\text{with DRA}}}{\Delta P_{\text{without DRA}}}$$

Experimental Setup

The experiments have been performed in an 18-m long, 10-cm-dia, low-pressure, inclinable flow loop shown in Fig. 1. A water-oil mixture is stored in a 1.2-m^3 stainless steel storage tank (A). The tank is equipped with stainless steel heating and cooling coils to maintain a constant temperature. The oil-water mixture is then moved through the system using a 76-hp stainless steel, low-shear progressive cavity pump (B). The variable speed pump controls the liquid flow rate.

Carbon dioxide gas from a 20,000 kg storage tank (D) is introduced into the system through a 5-cm-dia black pipeline. The gas flow rate is metered using a variable area flow meter. The oil-water-gas mixture is mixed at a tee junction (C). The

Contributed by the Petroleum Division and presented at the Twentieth Annual Energy-Sources Technology Conference and Exhibition, Houston, Texas, February 1–3, 1999, of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. Manuscript received by the Petroleum Division, August 5, 1998, revised manuscript received February 13, 1999. Technical Editor: J. P. Brill.

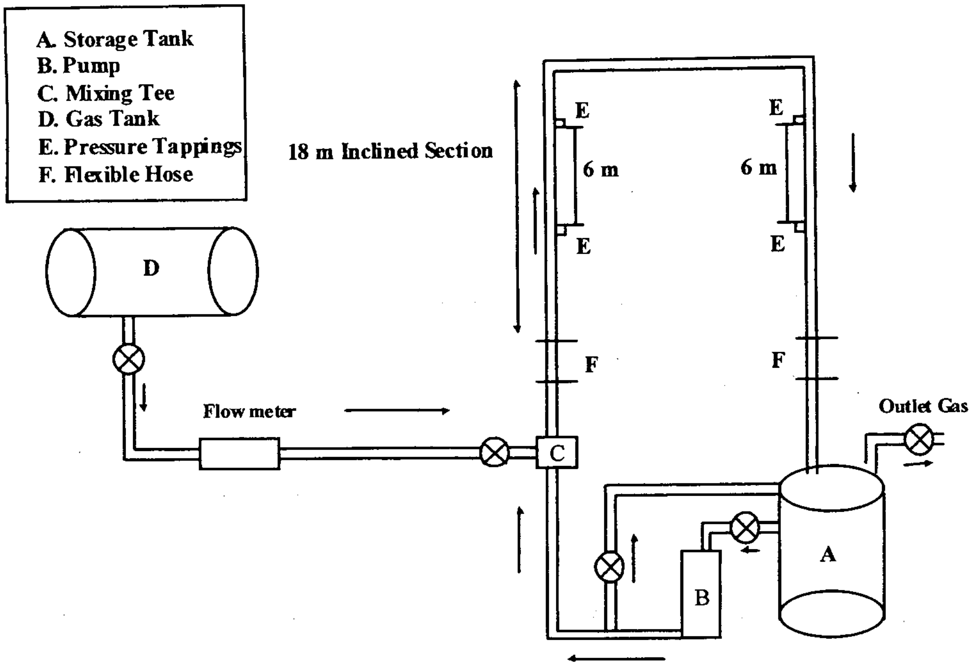

Fig. 1 Experimental layout of the flow loop

multiphase mixture then flows through a 3-m long flexible hose (F), which allows the inclination to be set at any angle. The multiphase mixture then flows into an 18-m long plexiglass pipeline (10-cm diameter) where flow pattern, pressure gradient, and slug characteristics are measured. The multiphase mixture then returns to the tank. Gas is vented to the atmosphere and the liquid is recirculated.

A Panasonic super-VHS camera is used to obtain detailed data regarding slug characteristics such as slug translational velocity, slug frequency, and the height of the liquid film. The pressure gradient is measured along a 6-m length of the pipeline for both upward and downward flow using pressure tappings (E) connected to Sensotec pressure transducers.

Superficial liquid velocities between 0.5 and 3 m/s and superficial gas velocities between 2 and 10 m/s were examined. Oil with a viscosity of 2.5 cP at room temperature was used in this study. Carbon dioxide was used as the gas. A water cut of 50 percent was used for the experiments. The temperature was maintained at 25°C. Oil soluble DRA was used. The effectiveness of DRA was studied for three concentrations (0, 10, and 50 ppm).

Results

Figure 2 shows a plot of effectiveness for 50 ppm DRA concentration at superficial liquid velocities between 0.5 and 3 m/s and superficial gas velocities between 2 and 10 m/s in 2 deg downward inclined pipes. It can be seen from this figure that DRA was effective at all superficial liquid and gas velocities. At a superficial liquid velocity of 0.5 m/s and superficial gas velocities of less than 4 m/s, stratified flow regime is observed and the effectiveness is over 90 percent. The effectiveness generally decreases with increasing superficial liquid velocity at the same superficial gas velocity. For example, the effectiveness at a superficial gas velocity of 2 m/s decreases from 92 to 34 percent with increasing superficial liquid velocity from 0.5 to 3 m/s. At superficial gas velocity of 4 m/s and higher, slug flow regime occurs at all superficial liquid velocities and the effectiveness is lower than 50 percent.

Figure 3 shows a plot of the pressure gradient results with 10 and 50 ppm DRA concentrations in 15-deg upward inclined pipes at superficial liquid velocity of 0.5 m/s. It is seen that the pressure gradient decreases with DRA concentrations at all superficial velocities. The pressure gradient without DRA increases from 500 to 1417 Pa/m with an increase of the superficial gas velocity from 2 to 8 m/s. The pressure gradient decreased from 1417 to 1333 Pa/m as the superficial gas velocity increased from 8 to 10 m/s. This is due to a transition to pseudo-slug flow. The pressure gradient decreases from 767 to 533 Pa/m, from 833 to 567 Pa/m and from 1417 to 1250 Pa/m at superficial gas velocities of 4, 6, and 8 m/s, respectively, when 10 ppm DRA is added. A much better performance is obtained with addition of 50 ppm DRA. The pressure gradient decreases from 500 to 167 Pa/m, from 767 to 400 Pa/m, from 833 to 500 Pa/m, from 1417 to 1083 Pa/m, and from 1333 to 1167 Pa/m at superficial gas velocities of 2, 4, 6, 8, and 10 m/s, respectively. These correspond to an effectiveness of 67, 48, 40, 24,

Nomenclature

$\Delta P/L$ = pressure gradient, Pa/m
i.d. = inside diameter, m
DRA = drag-reducing agents
V_{sl} = superficial liquid velocity, m/s
V_{sg} = superficial gas velocity, m/s
V_t = slug translational velocity, m/s
V_{LF} = velocity of film ahead of slug, m/s
h_{eff} = effective height of film
g = acceleration due to gravity, m/s^2
Fr = Froude no.
$\Delta P_{\text{without DRA}}$ = pressure drop without presence of DRA, Pa
$\Delta P_{\text{with DRA}}$ = pressure drop with presence of DRA, Pa

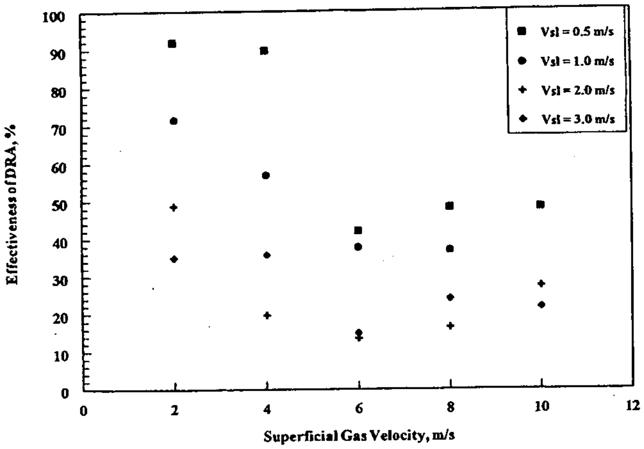

Fig. 2 Effectiveness of 50 ppm DRA—2-deg downward flow

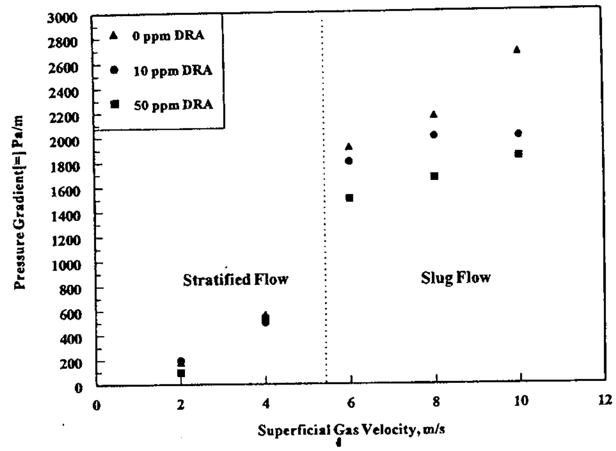

Fig. 5 Pressure gradient versus superficial gas velocity—V_{sl} = 2.0 m/s, 15-deg downward flow

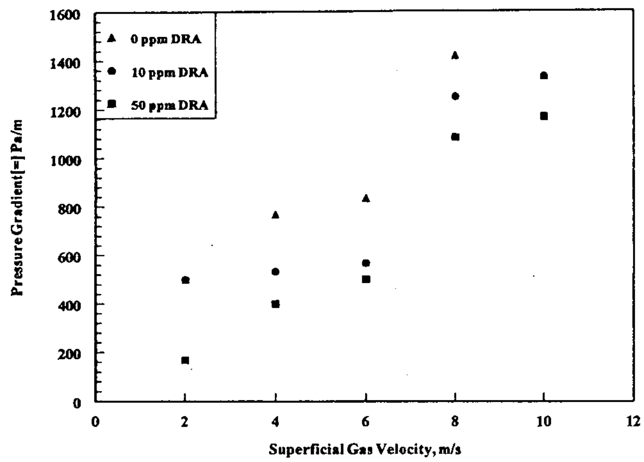

Fig. 3 Pressure gradient versus superficial gas velocity—V_{sl} = 0.5 m/s, 15-deg upward flow

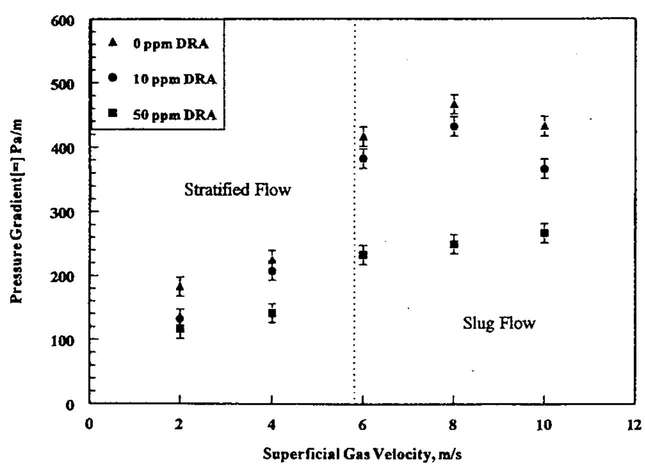

Fig. 4 Pressure gradient versus superficial gas velocity—V_{sl} = 0.5 m/s, 15-deg downward flow

and 13 percent, respectively. It can be seen from these results that the effectiveness of DRA at lower superficial gas velocities is much greater than that at higher superficial gas velocities.

Results of the pressure gradient for stratified flow and slug flow in 15-deg downward inclined pipes at superficial liquid velocity of 0.5 m/s are shown in Fig. 4. At the superficial gas velocity of less than 6 m/s, stratified flow regime is observed. At a superficial gas velocity of 2 m/s, the pressure gradient for stratified flow decreases from 183 to 133 Pa/m for a concentration of 10 ppm DRA and to 117 Pa/m when increasing DRA concentration to 50 ppm. These correspond to an effectiveness of 27 and 36 percent, respectively. Slug flow regime occurs at a superficial gas velocity of greater than 6 m/s. At superficial gas velocities of 6 and 8 m/s, the pressure gradient decreases from 417 to 383 Pa/m and from 467 to 433 Pa/m as 10 ppm DRA was added. When the DRA concentration is increased to 50 ppm, there is a significant increase in performance. At the same superficial gas velocities, the pressure gradient decreases from 417 to 233 Pa/m and from 467 to 250 Pa/m with 50 ppm DRA concentration. It can be seen from Figs. 3 and 4 that the pressure gradient in upward flow is greater than that in downward flow for the same conditions. At a superficial gas velocity of 6 m/s, the pressure gradient for upward flow is 833 Pa/m, while the pressure gradient for downward flow is 417 Pa/m. This is because liquid film thickness for upward is higher than that for downward flow.

Figure 5 shows a plot of pressure gradient results with DRA concentrations at a superficial liquid velocity of 2.0 m/s in 15-deg downward inclined pipes. At a superficial gas velocity of greater than 5 m/s, slug flow regime is observed. At superficial gas velocities of 6, 8, and 10 m/s, the pressure gradient decreases from 1917 to 1800 Pa/m, from 2167 to 2000 Pa/m, and from 2667 to 2000 Pa/m, respectively, as 10 ppm DRA is added. When the concentration of DRA is increased to 50 ppm, the pressure gradient decreases from 1917 to 1500 Pa/m, from 2167 to 1667 Pa/m and from 2667 to 1833 Pa/m, respectively, at the same superficial gas velocity.

Figure 6 shows a plot of slug translational velocity versus superficial gas velocity for each DRA concentration at a superficial liquid velocity of 0.5 m/s in 15-deg upward inclined pipes. It is seen that DRA does not have any effect on slug velocity. Slug velocity increases from 3.2 to 12.2 m/s with an increase of superficial gas velocity from 2 to 10 m/s.

Figure 7 shows a plot of the effect of DRA on slug frequency at superficial liquid velocity of 1 m/s in 15-deg upward inclined pipes. The slug frequency does not change much as 10 ppm DRA is added. However, it is seen that the slug frequency decreases for 50 ppm DRA concentration. The slug frequency decreases from 71 to 64 slugs/min, from 68 to 54 slugs/min, and from 63 to 48 slugs/min at superficial gas velocities of 2, 4, and 6 m/s, respectively. At higher superficial gas velocity of 8 m/s, the slug frequency does not change.

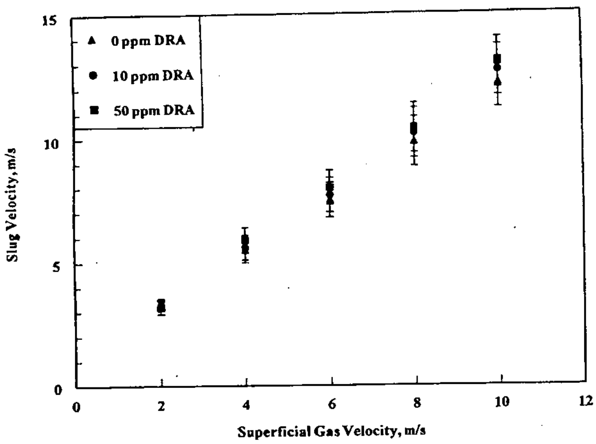

Fig. 6 Slug velocity versus superficial gas velocity—V_{sl} = 0.5 m/s, 15-deg upward flow

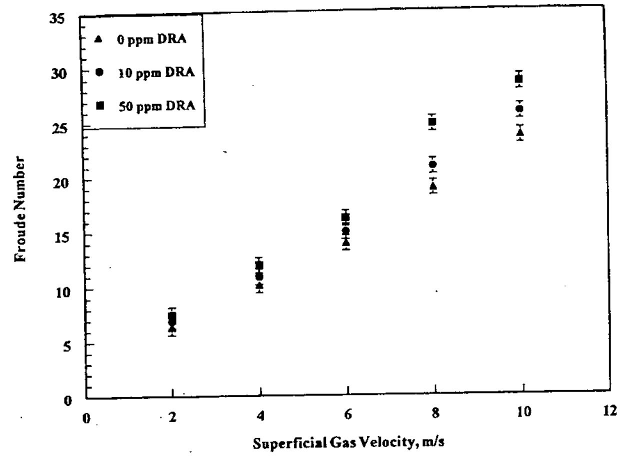

Fig. 9 Froude number versus superficial gas velocity—V_{sl} = 1.0 m/s, 15-deg upward flow

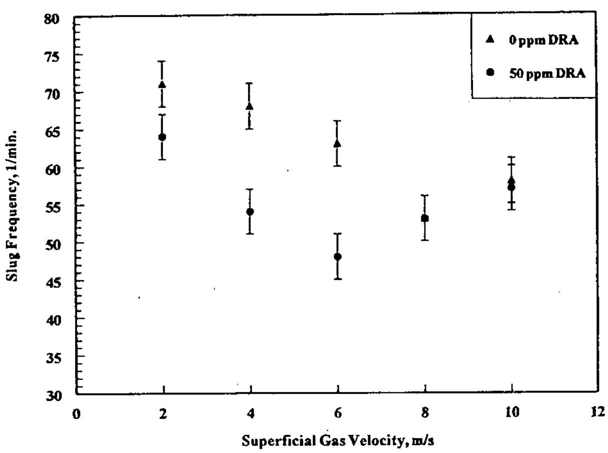

Fig. 7 Slug frequency versus superficial gas velocity—V_{sl} = 1.0 m/s, 15-deg upward flow

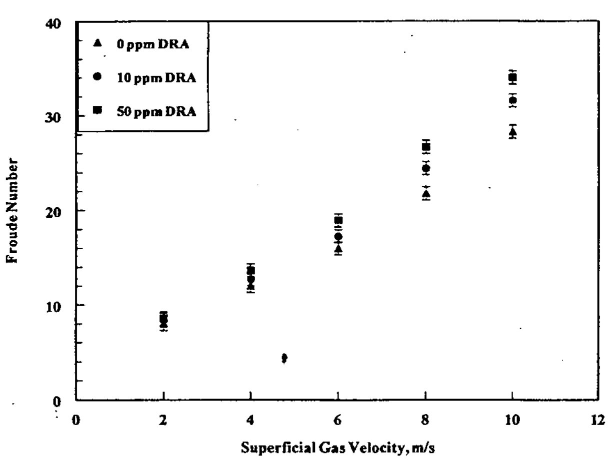

Fig. 8 Froude number versus superficial gas velocity—V_{sl} = 0.5 m/s, 15-deg upward flow

Figures 8 and 9 show plots of Froude number versus superficial gas velocity with DRA concentrations at superficial liquid velocities of 0.5 and 1 m/s in 15-deg upward inclined pipes. It is seen that Froude number increases with DRA concentrations in all cases. This is due to the fact that the height of the liquid film is reduced and the liquid is spread around the pipe wall as DRA concentration is added, which leads to an increase of Froude number. For example, the height of the liquid film at a superficial liquid velocity of 0.5 m/s and a superficial gas velocity of 4 m/s decreases from 4.1 to 3.8 cm and from 4.1 to 3.6 cm with 10 and 50 ppm DRA concentrations, respectively. It is seen from Fig. 8 that Froude number at a superficial gas velocity of 6 m/s increases from 16 to 17.3 and from 16 to 19 for DRA concentrations of 10 and 50 ppm DRA, respectively. It is seen from Fig. 9 that Froude number at a superficial gas velocity of 4 m/s increases from 10.2 to 10.9 and from 10.2 to 12, respectively, when 10 and 50 ppm DRA are added. It is also seen that Froude number at a superficial liquid velocity of 0.5 m/s is higher than that at a superficial liquid velocity of 1.0 m/s in all cases. The reason is that the liquid at low liquid velocity can roll back down the pipe due to gravity forces.

Conclusions

Experiments have been carried out to examine the performance of DRA in three phase (50 percent oil-50 percent water-carbon dioxide gas) flow in 10 cm i.d. upward and downward inclined pipes.

The pressure gradient for stratified flow was decreased by 92 percent with 50 ppm DRA concentration at a superficial liquid velocity of 0.5 m/s and superficial gas velocity of 2 m/s in 2-deg downward inclined pipes. The effectiveness of DRA generally decreases with increasing superficial liquid velocity for same superficial gas velocity.

The DRA was effective in reducing the pressure gradients in multiphase flow in 15-deg upward and downward inclined pipes. A much better performance with 50 ppm DRA is obtained under all conditions studied. At the superficial liquid velocity of 0.5 m/s and superficial gas velocity of 4 m/s, the effectiveness of DRA was 30 and 48 percent with 10 and 50 ppm, respectively.

DRA does not have any effect on the slug velocity. The slug frequency does not change much for a concentration of 10 ppm DRA. However, the slug frequency decreases at the superficial liquid velocity of 1 m/s and superficial gas velocities of less than 6 m/s when the DRA concentration is increased to 50 ppm.

The height of the liquid film decreases with DRA concentration, which leads to an increase in Froude number. Froude number increases from 13.9 to 15 and from 13.9 to 16.2 for DRA concentrations of 10 ppm and 50 ppm.

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The software is of great value to all engineers, researchers, educators, and journal editors. An engineer can use it to find if any research has been done on a problem of interest. For example, one author of this review was recently involved in a project about the vibration of electric motors.

Using the software, a query made with the keywords 'vibration,' 'electric,' and 'motor' revealed 17 papers on the subject.

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Reprinted from Appl Mech Rev vol 51, no 7, July 1998.