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The Improvement of a Commercially Used Digital Pulsation Simulation

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ABSTRACT

A paper was presented in 1989 by H. Kammin describing the improvement in the damping model of a frequency domain digital pressure pulsation simulation. In this paper, the 1989 method has been incorporated into a computer software system called DPULS(c), and further improvements have been made which include real valve modeling and the interaction between valve element motion and pressure pulsations in cylinder gas passages. The simulation is currently being used to perform piping pulsation studies on a commercial basis.

INTRODUCTION

Since the 1989 version of the frequency domain pulsation simulation (now called DPULS(c)), further improvements have been made to the simulation. The first improvement has been to include advanced cylinder and valve modeling with an option for cylinder/valve model interaction with pressure pulsations. Another improvement has been to add a post-processor to facilitate problem solving and report generation.

This paper will present the improvements to the cylinder/valve modeling and the effects of pulsation interaction modeling. Also, a comparison of DPULS(c) results with pressure pulsation test data will be given for two different compressor applications.

IMPROVED CYLINDER MODEL

Cylinder Modeling General Information

The 1989 version of the simulation used a simple cylinder flow model based on the piston speed without taking into account the valves. In order to accurately model the interaction between the gas passage pulsations and the cylinder model, an improved cylinder model was needed. This cylinder model includes valve effects.

The improved cylinder model in the DPULS(c) program is a mathematical model of the internal cylinder processes that create and influence the pulsations in the piping network being studied. This cylinder model creates the forcing function for the piping network. In the improved cylinder model described in the following section, the motion of the valve moving elements are calculated and the pulsations can interact and influence that motion.

The cylinder model is a time domain model. This model takes in information about the compressor and the cylinder (stroke, con. rod. length, etc.), information about the gas in the cylinder (pressure, temperature, gas composition, etc.), and information about the valve (size, springs, flow area, etc.) for the cylinder. The cylinder model then calculates the cylinder gas state throughout the cycle of the compressor including the motion of valve elements and the amount of gas flowing into or out of the valves. The resulting function of flow versus time in and/or out of the valves is then transformed to the frequency domain which becomes the forcing function for the pulsation analysis (which is done in the frequency domain).

The method for the cylinder model time domain solution is based on a standard technique (Woollatt, 1973) and is used on a commercial basis for dynamic valve analysis (DVA). The calculation of gas properties (critical pressure, critical temperature, compressibility, ratio of specific heats, and volumetric exponent) is based on standard programming and a data base of 469 pure gas components used for commercial performance prediction. Both of these analytical tools have been found to be reliable and accurate and require no further explanation. What is unique to the DPULS(c) program and does require explanation is the INTERACTION between the time domain solution for the cylinder and the frequency domain solution for the piping analysis.

Valve/Piping Interaction

Before the improved cylinder model could be implemented, the following issues related to valve/piping interaction had to be resolved:

A. Where should the cylinder model end and piping model start? The following were considered:

1. AT THE CYLINDER FLANGE CONNECTION. In this case, the cylinder model extends beyond the valves and into the cylinder flow passages and the piping model is just in the piping system. In this case, the cylinder model would lump all the valves into a single cylinder flow source.

2. AT EACH VALVE. In this case, the cylinder model ends at the valves with each valve considered as a flow source. The piping model would extend beyond the piping system into the cylinder flow passages and up to each valve. In this case, the piping model could influence individual valve moving elements, but the flow for all the elements is lumped into a single flow source.

3. AT EACH VALVE MOVING ELEMENT. In this case, the cylinder model ends at the valve as in 2 above, but the piping model would include pipe elements up to each individual plate or valve moving element. In this case, each valve moving element is an independent flow source.

For the current version of the DPULS(c) program, approach 2 above has been taken.

B. Should the pulsations from the piping model be extended into and reflected from the interior of the cylinder while the valves are open?

For the current version of DPULS(c) this effect is ignored. The piping pulsations only influence the cylinder model by changing the motion of the valve moving elements, and by changing the pressure seen by the gas from beyond the valve (when the valve is open). The cylinder model in turn only influences the piping model by changing the amount and timing of the flow into the piping from the valve.

C. If the valve/piping interaction is to be coupled, then how would a solution be achieved?

The flow from the cylinder model is affected by the pressure pulsations in the piping model (just beyond the valve, by influencing the motion of the valve moving element and the flow of the gas. However, the pulsations in the piping are actually caused by the flow from the cylinder model. Therefore, the two models are considered coupled, and the coupling occurs at the valve/piping interface. The valve/piping interface is just beyond the valve moving elements and at the beginning of the cylinder flow passages. Since both the cylinder model and the piping model estimate the flow and pressure of the gas at the interface, the DPULS(c) program considers a solution to have been achieved when both models agree on the frequency domain of the gas state at the interface (unless valve/piping interaction is not desired for the study).

Solution Procedure

With these issues resolved, the solution procedure for the current version of DPULS(c) proceeds for a given cylinder as follows:

1. The program starts with the performance prediction stage pressure. This is considered a constant pressure just beyond the cylinder's valves. With this constant pressure, the cylinder model is run to find the motion of the each element of each valve and the resultant flow versus time from each valve. This is all done in the time domain.

2. The time domain flow through each valve is transformed into the frequency domain.

3. The frequency domain flow forcing functions are used to find the pressure and flow throughout the piping network by the frequency domain solution.

4. The frequency domain solution is transformed back to the time domain at each valve/piping interface.

5. The pressure versus time is now used in the cylinder model. The cylinder model calculates the motion of the elements and flow from the valves considering varying pressure of the gas just beyond the valve (unlike step 1).

6. The process now repeats starting with step 2. A solution is achieved when the frequency domain of the gas state at the valve/piping interfaces has converged (within a tolerance).

Cylinder Model Results

Figures 1 and 2 are p-v cards from two cylinders in service. The solid line trace is the actual cylinder p-v data. The dashed line is the cylinder model's prediction without interaction with the piping

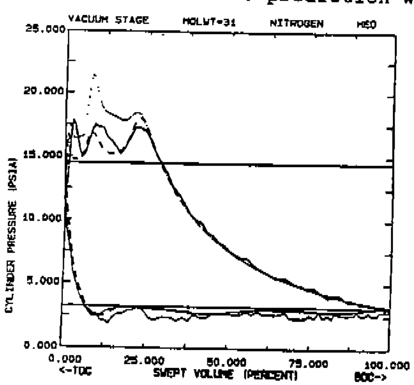

FIGURE 1. P-V CARD 1ST STAGE

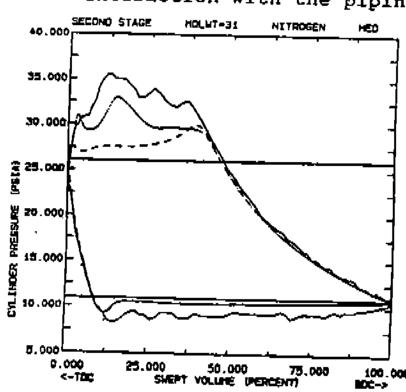

FIGURE 2. P-V CARD 2ND STAGE

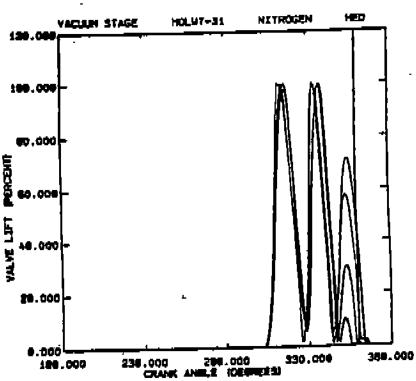

FIGURE 3. VALVE MOTION 1ST STG

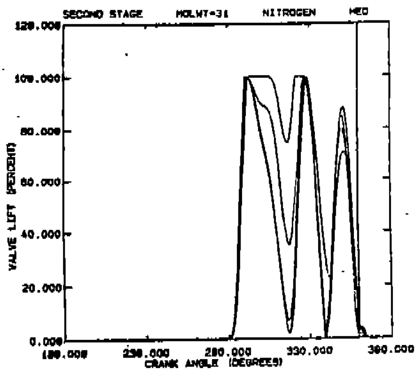

FIGURE 4. VALVE MOTION 2ND STG

model. The dotted line is the cylinder model's prediction with interaction with the piping model.

Figures 3 & 4 show the predicted valve moving elements motion with the valve/piping interaction for the cylinders in Figures 1 & 2.

PULSATION INTERACTION EFFECTS

Using the improved cylinder model in DPULS(c), it is clear that the valve/piping interaction has a significant effect on the cylinder pressure and on the pulsations in the cylinder passages. Next, the effect of valve/piping interaction on the pulsations in the piping beyond the cylinder passage and pulsation vessel must be assessed.

In this case, a different piping system was analyzed with DPULS(c) and the results evaluated for changes in piping pulsations with and without the valve/piping interaction option. Figures 5 and 6 illustrate the effects of interaction on p-v card and flow through the valves. Tables 1 and 2 show the effects on pulsations at the valves and pulsations at the line connection of a typical compressor.

Figure 5 shows the predicted p-v card with and without piping interaction. The solid line p-v card is with no interaction with the piping model, the dashed line p-v card is with interaction, and the dashed line that extends across the swept volume is the time domain pressure in the discharge gas passage. The effects on horsepower and capacity can be readily observed. In this case the pulsation interaction tends to increase the horsepower requirement.

Figure 6 shows the time domain flow rate through a valve for the same cylinder shown in Figure 5. The solid line is the flow versus time with no interaction with the piping model, and the dashed line is the flow with interaction. In this case, it is shown that the piping interaction has had a small effect on the average flow rate, but the timing and shape of the curve (and hence the forcing function to the piping model) has been altered.

Given the effect of valve/piping interaction on the piping model forcing function, changes in the piping pulsations due to these effects are to be assessed. This is done by using the DPULS(c) program to calculate the piping pulsations and compare the results with and without the valve/piping interaction.

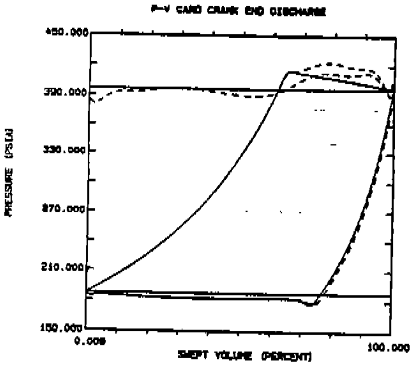

FIGURE 5. TYPICAL P-V CARD

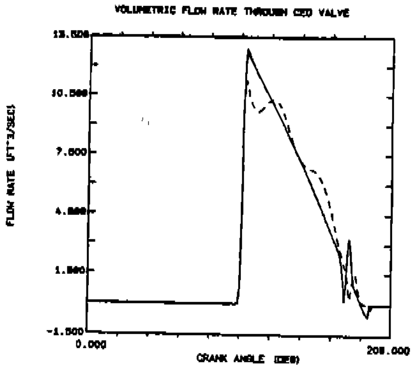

FIGURE 6. TYPICAL FLOW VS. TIME

Table 1 shows a comparison of the pulsations at the valves with and without interaction. In comparison to an allowable level of 10 percent of line pressure, the pulsations have changed only a few percent (except for one point with 11.2 percent change).

TABLE 1. PRESSURE PULSATIONS AT THE VALVES

HARMONIC NUMBER	PULSE (P-P) NO INTERACTION	PULSE (P-P) INTERACTION	(%) CHANGE	(%) CHANGE RELATIVE TO ALLOWABLE
1	4.01	4.13	3.0	0.3
2	14.52	14.61	0.6	0.2
3	7.88	8.14	3.3	0.7
4	15.20	14.45	-4.9	-1.9
5	8.61	7.41	-13.9	-3.0
6	2.63	1.85	-29.7	-2.0
7	3.76	2.93	-22.1	-2.1
8	2.12	2.06	-2.8	-0.2
9	3.39	3.33	-1.8	-0.2
10	5.52	5.37	-2.7	-0.4
11	1.77	1.31	-26.0	-1.2
12	7.81	3.39	-56.6	-11.2

Table 2 shows a comparison of the pulsations at the vessel line connection with and without piping interaction. These results show an even smaller effect on the pulsation. The change relative to a 2 percent of line pressure allowable level was less than one percent (the line pressure was 396 PSIA):

TABLE 2. PRESSURE PULSATIONS AT THE LINE CONNECTION

HARMONIC NUMBER	PULSE (P-P) NO INTERACTION	PULSE (P-P) INTERACTION	(%) CHANGE	(%) CHANGE RELATIVE TO ALLOWABLE
1	0.49	0.53	8.2	0.5
2	2.34	2.36	0.9	0.3
3	0.42	0.44	4.8	0.3
4	0.67	0.64	-4.5	-0.4
5	**	**	--	--
6	**	**	--	--
7	**	**	--	--
8	**	**	--	--
9	**	**	--	--
10	**	**	--	--
11	**	**	--	--
12	**	**	--	--

** PULSATIONS UNDER 0.1% OF LINE PRESSURE

From this case, it is clear that the valve/piping interaction has not had a significant effect on the valve and line connection piping pulsations. Therefore, based on this information the extra time involved in calculating the pulsation effects are not necessary to adequately perform a piping network pulsation study (unless evaluating performance changes). Note that in this situation the pulsation vessel was more than adequate to isolate the gas passage pulsations from the piping pulsations.

TEST DATA COMPARISONS OF PRESSURE PULSATIONS IN PIPING SYSTEMS

Test Case 1

Figure 7. shows a sketch of the first stage suction piping of a natural gas injection facility.

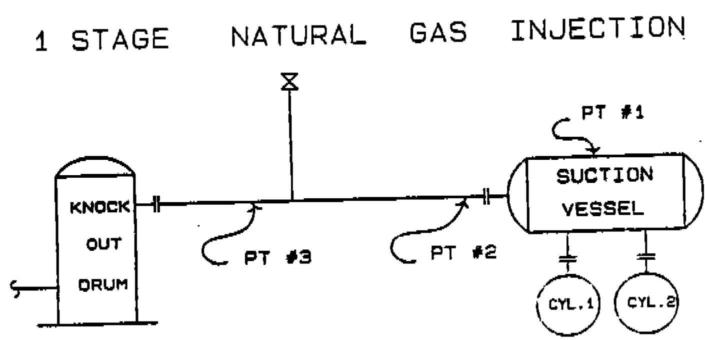

FIGURE 7. PIPING SKETCH TEST CASE 1.

Test data taken at this facility was used to compare with DPULS(c) and is shown in Figures 8 through 10. The simulation was run with a 10% speed sweep to account for small variations in gas composition, temperature, pressure and piping geometry. Three test points are shown; Figure 8 at the center of the pulsation vessel, Figure 9 at the line connection of the pulsation vessel, and Figure 10 at approximately one third the way from the pulsation vessel to the knock out drum. The test data is indicated by circles on the plots while the simulation data is represented by the solid lines.

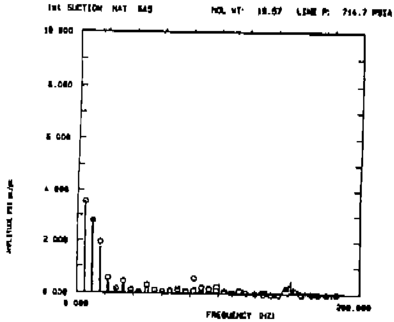

FIG. 8. PULSATIONS PT #1

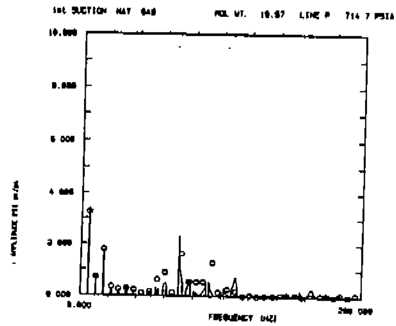

FIG. 9. PULSATIONS PT #2

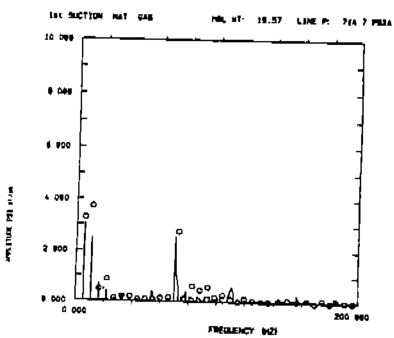

FIG. 10. PULSATIONS PT #3

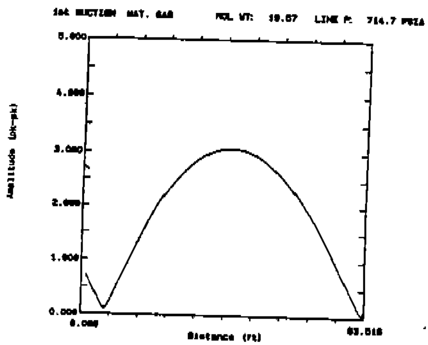

FIG. 11. MODE SHAPE 2ND HARMONIC

Although, Pt #3 on the sketch (Figure 10) shows a fairly significant difference in amplitude at the second order of running speed, the results show excellent agreement between DPULS(c) and the actual measurements taken. On Figures 8 to 10, a resonance is observed at the second order pulsations. This appears to indicate a typical half wave resonance for an open-open ended pipe. Using the DPULS(c) post-processor, the second order pressure pulsation amplitude versus distance was plotted for the piping between the volumes (Figure 11). A half-wave resonance between the suction vessel and the knock out drum can be seen at second order running speed.

Test Case 2

Figure 12 shows a sketch of the 2nd stage discharge piping of a reciprocating compressor that compresses a hydrogen-nitrogen mixture.

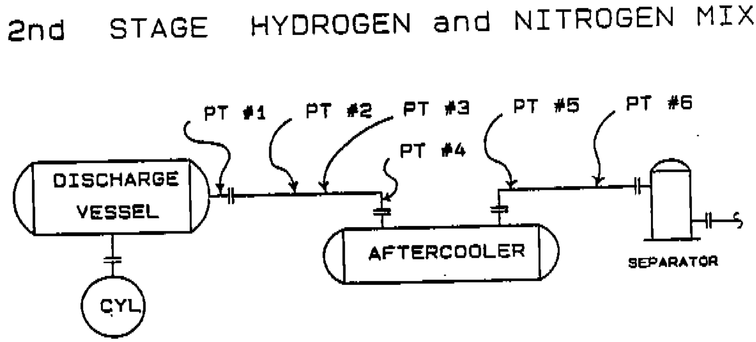

FIGURE 12. PIPING SKETCH TEST CASE 2.

DPULS(c) was used to simulate the pressure pulsations and the results are shown in Figures 13 to 18. Test data is shown in the plots on the left, while the simulation results are shown on the right.

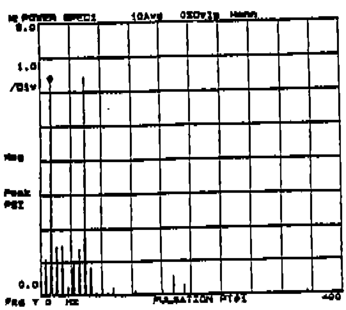

FIGURE 13A

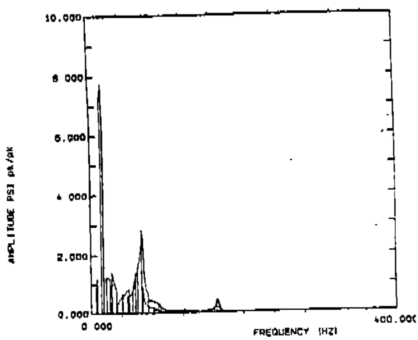

FIGURE 13B

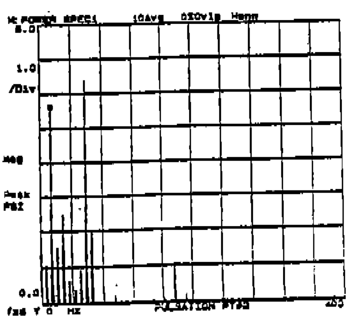

FIGURE 14A

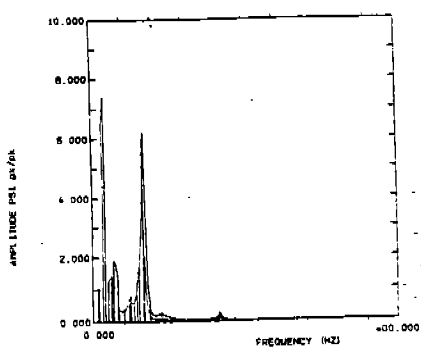

FIGURE 14B

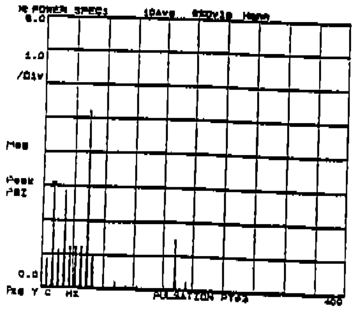

FIGURE 15A

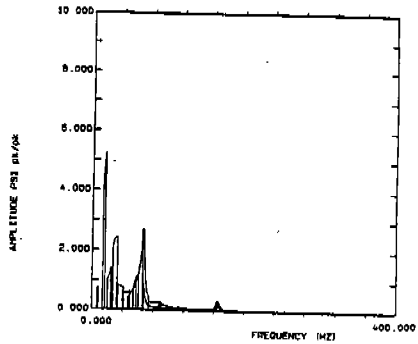

FIGURE 15B

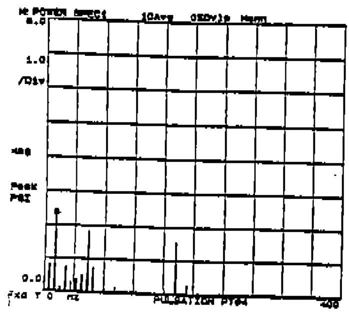

FIGURE 16A

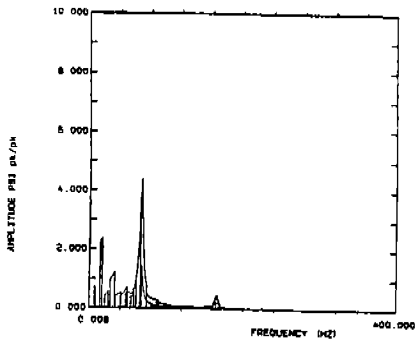

FIGURE 16B

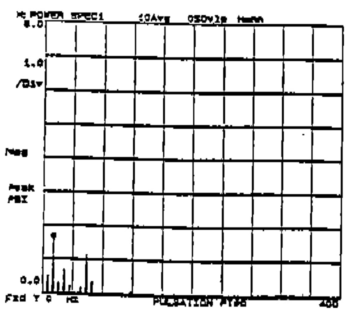

FIGURE 17A

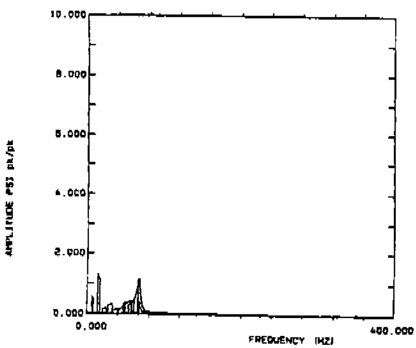

FIGURE 17B

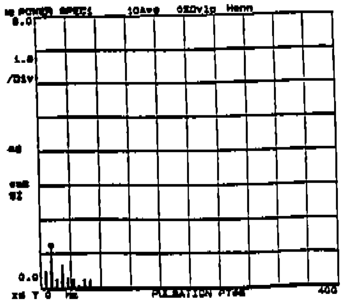

FIGURE 18A

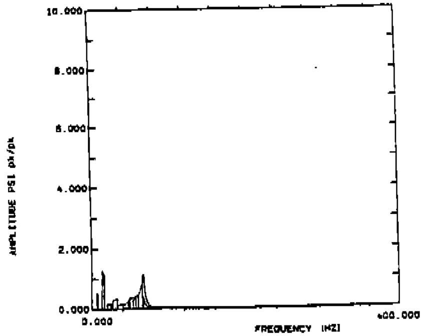

FIGURE 18B

CONCLUSIONS

In this paper, the improvements to a commercially used software system for piping pulsation simulation have been presented. The first improvement is an advanced cylinder model that permits the studying of valve/piping interaction. This paper has shown that this valve/piping interaction is important for simulating the internal cylinder pressure and the pulsations in the cylinder gas passages. However, for a few typical case studies, this paper has shown that this interaction is not important for simulating the pulsations in the piping system. The second improvement to the software system is the addition of a post-processor. This paper has shown numerous outputs from this post-processor including harmonic spectrum plots, amplitude versus distance plots, p-v cards, and valve motion plots. These improvements have permitted the DPULS(c) program to become an analytical tool for everyday use in the design of reciprocating compressor systems for customers world-wide.

Finally, the DPULS(c) software system is in a program of continuous improvement. In the future, the program is to be enhanced to include parallel flows, enhanced piping data input programming, and evaluation of interaction effects on performance.

ACKNOWLEDGEMENTS

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