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Computer Animation of a Compressor: A Teaching Aid*

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An animation tool for teaching about reciprocating compressors was developed on an IBM-compatible personal computer. This paper demonstrates how the fundamental working principles of a single-stage reciprocating compressor can be 'visually' brought home to students through the effects that computer animation can provide. It also illustrates how subject matter can be taught and learned more effectively and efficiently through the use of animation. Mathematical modelling aspects of a reciprocal compressor will also be presented.

SUMMARY OF EDUCATIONAL ASPECTS OF THE PAPER

1. This paper describes the use of computers to assist teaching for third-year Bachelor of Engineering in Mechanical Engineering studies in Nanyang Technological University, Nanyang Avenue, Singapore 2263. The course code for the subject is M3002, entitled 'Thermo-Fluid II', sub-section 'Reciprocating compressors'.
2. This software is self-developed, mainly using FORTRAN.
3. This software is presently unique to the subject. However, because of the modular implementation of the computer program, it may be used with modifications in other similar areas of study.
4. The software is available in the school's computing laboratory, so that students may go through it at their own pace.
5. The benefits of the current software as compared to conventional approaches are that it is a visually based teaching package. It is able to illustrate fully the concepts involved in this area of study. It reduces the time students need to understand the concepts of this topic. Students can now see what happens with their own eyes rather than attempt to imagine what should happen.
6. The demonstration version of the software, which is good enough for teaching purposes, can be obtained from the author.
7. It requires a very short time to master the software. The demonstration version is designed to use in classroom teaching and also for students to go through it at their own pace.
8. The hardware requirement to run the software is an IBM-compatible personal computer with EGA or VGA (not CGA or monochrome) with maths coprocessor. It is recommended to run at least a 80386-based PC with maths coprocessor, with at least 640K of RAM memory. A 80386-based CPU or higher produces more realistic animation effects.

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NOMENCLATURE

A	area
c	effective damping
D	cylinder diameter
K	valve spring constant
M, m	mass
n	polytropic index
P	pressure
R_1	crank radius
R_2	connecting rod length
T	temperature
V	volume
x	valve displacement
F	force
(t)	a time function
$\cdot$	a time differential

Greek characters

γ	specific heat ratio
ω	valve natural frequency
$\bar{\omega}$	crank angular speed
ζ	valve damping coefficient
ρ	working fluid density
θ	crank rotation

Subscripts

d	down stream
u	up stream
v	valve
o	initial condition

INTRODUCTION

POSITIVE-displacement machines are generally included as part of the curriculum for undergraduate teaching in mechanical engineering. A single-stage reciprocating air compressor is often used to illustrate the concept of a positive-displacement machine. Under this topic, the compressor cycle as well as the effects of various design and operational parameters, such as discharge pressure, polytropic index and the effects of valves on the machine performance, are always introduced. Various performance parameters, such as the free air delivery, the volumetric efficiency and the power input, are normally highlighted. In some cases, the subject matter also forms a laboratory exercise so that students can have hands-on experience of the operation of such a machine.

One learning difficulty that students encountered is that within the limited timescale available, they generally found it difficult to comprehend the concept of the subject matter clearly. They had problems appreciating and constructing correct mental images related to the subject matter. A normal laboratory session is not sufficient for visualizing the basic mechanisms of the machine, which is very important for a full understanding of the subject.

A computer animation of a single-stage air compressor provides an excellent learning aid. The visual impact that can be provided also makes the learning of the subject very interesting. Animation allows the internal mechanisms of the machine to be visualized during its operation. Using animation, changes in the state of the working fluid in the machine can be visualized with various colours and effects such as vibrations of the suction and discharge valves, the motions of crank mechanisms and piston as well as valve vibrations can all be watched. The animation tool also allows the step-by-step changes in the state of the working fluid in every process of a complete compressor cycle to be visualized and appreciated by the students. The effects of changing the design parameters affecting performance can be observed on the computer console. The complete animation tool consists of a pre-processor, which is a mathematical model that describes the basic working principles of the machine, and a post-processor, which animates the motion of the machine on the computer console.

MATHEMATICAL MODELLING

Figure 1 shows a schematic of a reciprocating compressor, indicating the major components of such a machine. The pre-processor consists of a collection of various mathematical models—a geometry model, a thermodynamics model, a valve dynamic model and a valve flow model—that describe the functions of these components. All these models are linked to simulate the basic working principles of the machine. While the inclusion of the leakage and the friction aspects into the model can greatly enhance the comprehension of the simulation, these are currently excluded in view of the massive computational time required. A simple model that permits the basic features to be studied is deemed sufficient. The various simulation models employed are described in the following sections.

Geometry model

This model describes the geometrical configuration of the machine. It relates the variation of the working chamber volume of the machine to the crank rotation and the speed of the machine. The variation of the volume with time can generally be

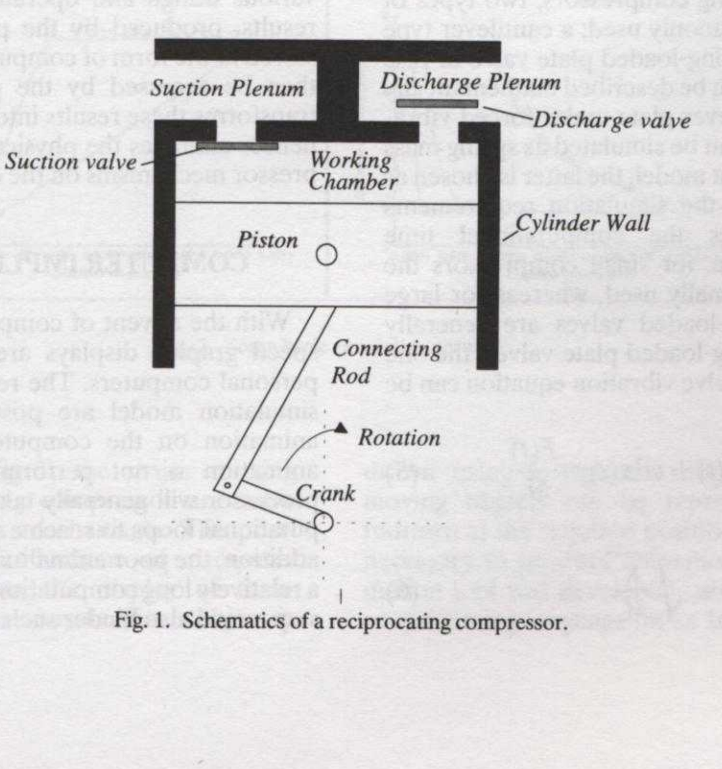


Fig. 1. Schematics of a reciprocating compressor.

expressed as a function of various geometrical parameters of the machine,

$$V(t) = f(V, D, R_1, R_2, \theta(t)) \quad (1)$$

For a simplified model, the crank speed can be assumed to be constant, and hence the angular rotation of the crank can be related to the mean angular speed of the compressor, i.e.

$$\theta(t) = \bar{\omega}(t) \quad (2)$$

Thermodynamic model

As a result of the changes of working chamber volume with crank rotation, the working fluid changes its properties during the machine operation. This model describes the variation of the state properties of the working fluid in the working chamber. The variation of the state properties of the working fluid can be obtained from the energy conservation approach, where the First Law of Thermodynamics is applied to the system [1]. For a simplified model, however, the computational time can be greatly reduced if the polytropic process is used to approximate the compression and expansion processes [2]. Hence the instantaneous working fluid pressure and temperature can be expressed as,

$$P(t) = P_o \left(\frac{m(t)}{\rho_o V(t)} \right)^n \quad (3)$$

$$T(t) = T_o \left(\frac{P(t)}{P_o} \right)^{\frac{n-1}{n}} \quad (4)$$

Valve dynamics model

This model describes the operation of the suction and discharge valve characteristics. It illustrates interactions between the valve vibrational characteristics and changes in fluid pressures. In reciprocating compressors, two types of valves are most commonly used: a cantilever type reed valve and a spring-loaded plate valve or disc valve. The former can be described mathematically as a vibrating cantilever plate under forced vibration [3]. The latter can be simulated as spring mass system. In the present model, the latter is chosen as it greatly simplifies the simulation requirements and hence reduces the computational time required. In practice, for small compressors the reed valves are normally used, whereas for large compressors spring-loaded valves are generally applied. In the spring-loaded plate valves, the one degree of freedom valve vibration equation can be expressed as

$$\ddot{x}(t) = 2\zeta\omega\dot{x}(t) + \omega^2 x(t) = \frac{F(t)}{M_v} \quad (5)$$

where

$$\omega = \sqrt{\frac{K}{M_v}} \quad (6)$$

$$\zeta = \frac{c}{2M_v\omega} \quad (7)$$

Note that in this case the maximum valve lift must be restricted to the maximum valve plate opening. For the case when the valve hits the valve stop, it can be assumed that all the kinetic energy of the valve plate has changed to heat energy and that the valve velocity is zero. Apart from showing the valve dynamic characteristics with interactions between fluid pressures and valve vibrations, this model provides instantaneous valve lifts, which are important in the consideration of the actual valve flow areas.

Valve flow model

The flow of working fluid through valve ports can be assumed to be a one-dimensional orifice flow. The active valve flow area must be determined from either the instantaneous valve annular area immediately under the valve plate or the valve port area, whichever restricts the flow more. The actual flow area can then be accounted for by introducing a discharge coefficient to the geometry area of the valve. If the working fluid can be assumed to be an ideal gas, as in the case of air compressors, the mass flow rate through the valve can be expressed as

$$\dot{m} = A_v P_u \sqrt{\frac{2\gamma}{(\gamma - 1)RT_u} \left(\left(\frac{P_d}{P_u} \right)^{\frac{2}{\gamma}} - \left(\frac{P_d}{P_u} \right)^{\frac{\gamma+1}{\gamma}} \right)} \quad (8)$$

For refrigeration compressors, a real gas simulation is required to describe the behaviour of the refrigerant vapour [4]. Choked flow and back flow can be accounted for by modifying eqn. (8) Equations (1)–(8) can be solved simultaneously. Figure 2 shows some basic simulation results for the various design and operating parameters. These results, produced by the pre-processor, may be stored in the form of computer data files. They can then be accessed by the post-processor, which transforms these results into computer images and hences animates the physical motions of the compressor mechanisms on the computer console.

COMPUTER IMPLEMENTATION

With the advent of computer technology, high-speed graphic displays are readily available on personal computers. The results produced by the simulation model are post-processed to create animation on the computer console. Real-time animation is not performed because the pre-processor will generally take a few iterative computational loops to reach a converged solution. In addition, the poor animation effects resulting from a relatively long computation time per computation step would also hinder such an implementation.

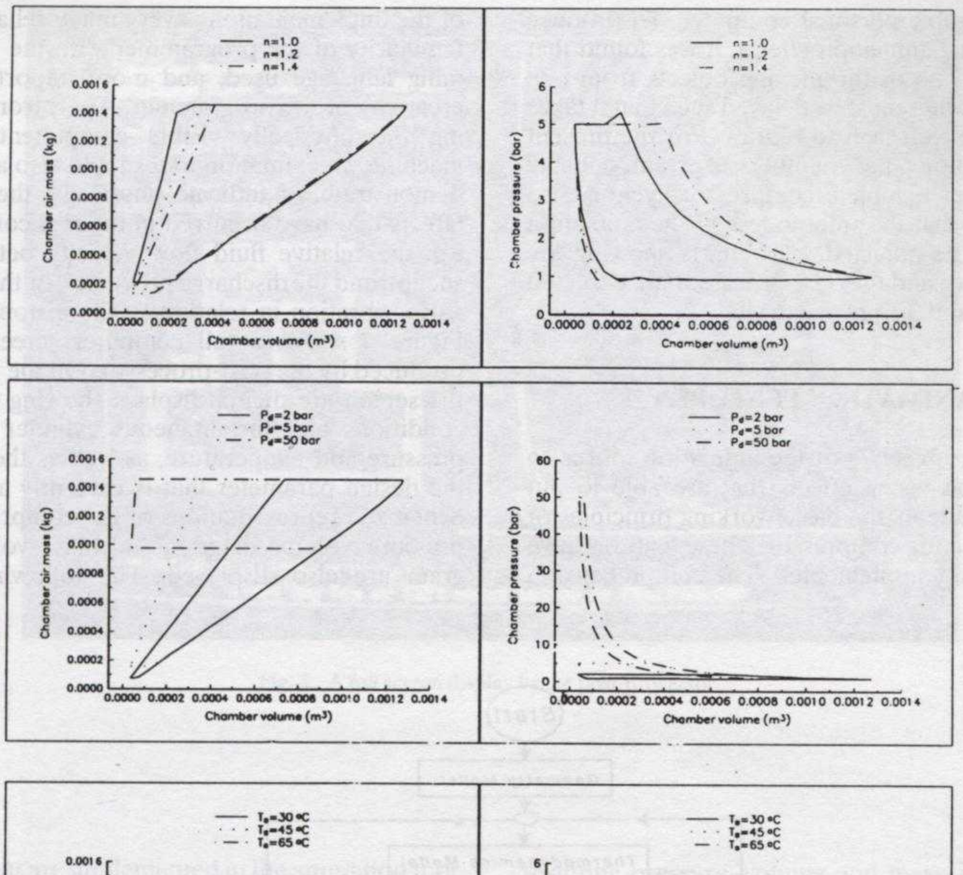
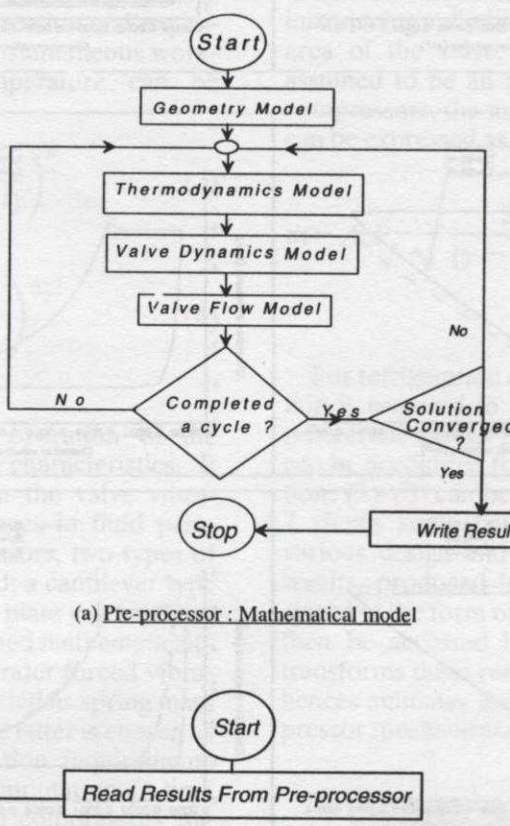


Fig. 2. Some basic simulation results.

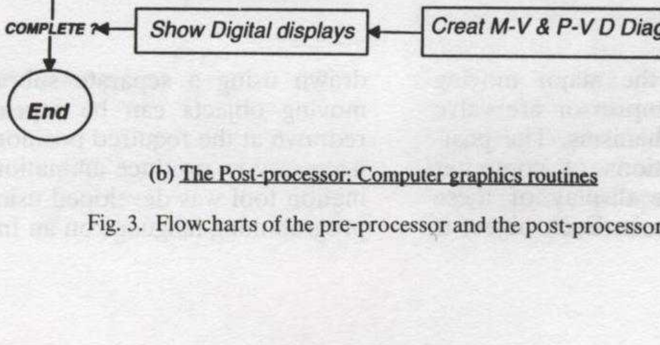
With reference to Fig. 1, the major moving objects in a reciprocating compressor are valve plates, piston and crank mechanisms. The post-processor consists of collections of computer subprograms to facilitate the display of these objects on the computer console. Each object is drawn using a separate subprogram such that moving objects can be repeatedly erased and redrawn at the required position as many times as necessary to produce animation effects. The animation tool was developed using the FORTRAN programming language on an Intel 486DX-based, IBM-compatible personal computer. To produce more realistic animation effects, it was found that the refresh rate of the moving objects from one frame to another must be delayed such that it takes longer to refresh than to redraw. For the present implementation, the number of frames being displayed per complete compressor cycle is also variable, so that the smoothness of the animation effects can be adjusted. Flowcharts showing the pre-processor and the post-processor are depicted in Fig. 3(a) and 3(b) respectively.

ANIMATION FEATURES

The main objective of the animation tool is to provide good visual effects that are able to put across to students the basic working principles of the reciprocating compressor. These features have to be carefully implemented. The comprehension of the implementation is very much reliant on the familiarity of the programmer with the programming language used, and more importantly the creativity of the programmer. Apart from animating the physically visible components of the machine, an animation tool should also attempt to demonstrate, or indicate physically, the invisible effects that have occurred in the real compressor, e.g. the relative fluid flow velocity between the suction and the discharge processes, or the detailed valve vibration in relation to the piston position. Figure 4 shows a full computer screen display produced by the post-processor. On the top left of the screen are digital displays showing operating conditions and instantaneous cylinder chamber pressure and temperature, as well as the value of the design parameter that is currently a variable. Schematic representations of the compressor, the pressure–volume diagram and mass–volume diagram are also displayed. The following shows



(a) Pre-processor : Mathematical model



(b) The Post-processor: Computer graphics routines

Fig. 3. Flowcharts of the pre-processor and the post-processor.

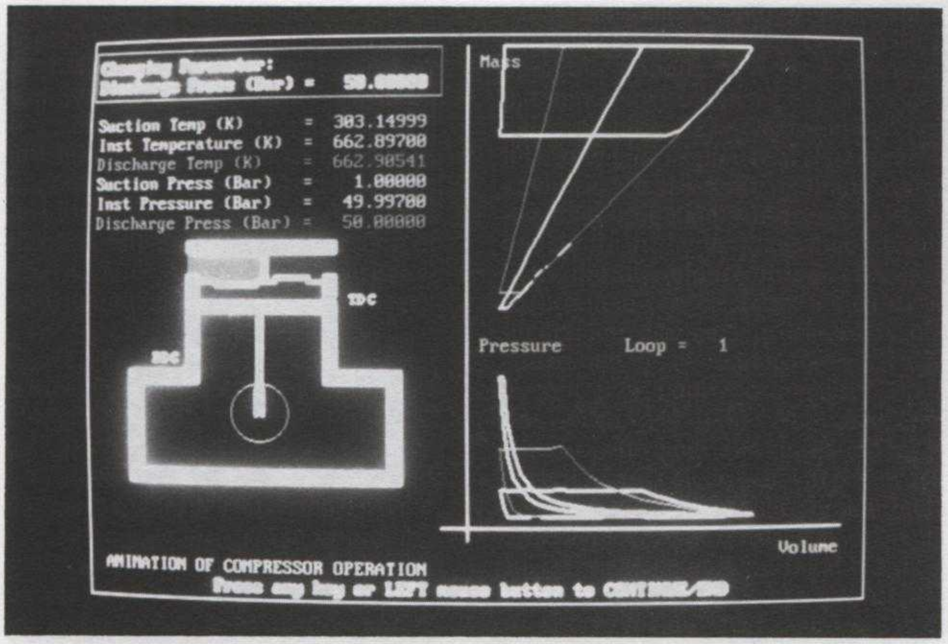


Fig. 4. A full screen display by the post-processor.

features that are implemented in the animation tool to exemplify the visual effects and to highlight the important concept of the operation of the machine.

Fluid pressure and temperature in the cylinder

Changes in the working fluid pressure and temperature are represented by changes in the colour of the working fluid in the cylinder. Green is used to represent suction temperature (low) and red to represent discharge temperature (hot). A series of colours is used to indicate the transition from low to high temperatures when piston changes and vice versa. To allow for closer examination of the changes of these two properties, numbers representing both the pressure and temperature are displayed in line with the operation of the machine (Fig. 4). These digital displays are particularly useful when the animation tool is chosen to execute under a slow-motion mode; detailed values of pressure and temperature can be read against the positions of the piston if required.

Valve vibration

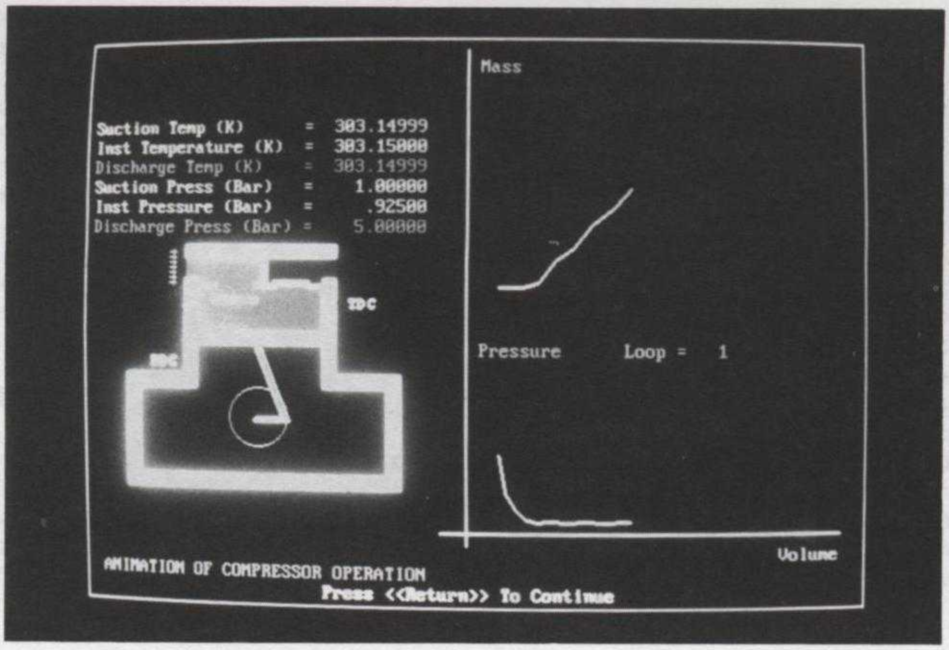
Amplitudes of valve vibration are demonstrated by showing the amplified valve lift to clarify the visual effects of valve vibration. The vibrational characteristic of the valve in relation to the piston position for various valve design parameters can be visualized clearly. The significance of valve spring stiffness, valve damping coefficient, valve port size, valve plate mass and their corresponding effects on the machine performance may be appreciated from the motion of the valve plate relative to piston position. These effects can also be seen on the resulting pressure–volume and mass–volume diagrams.

Valve flow

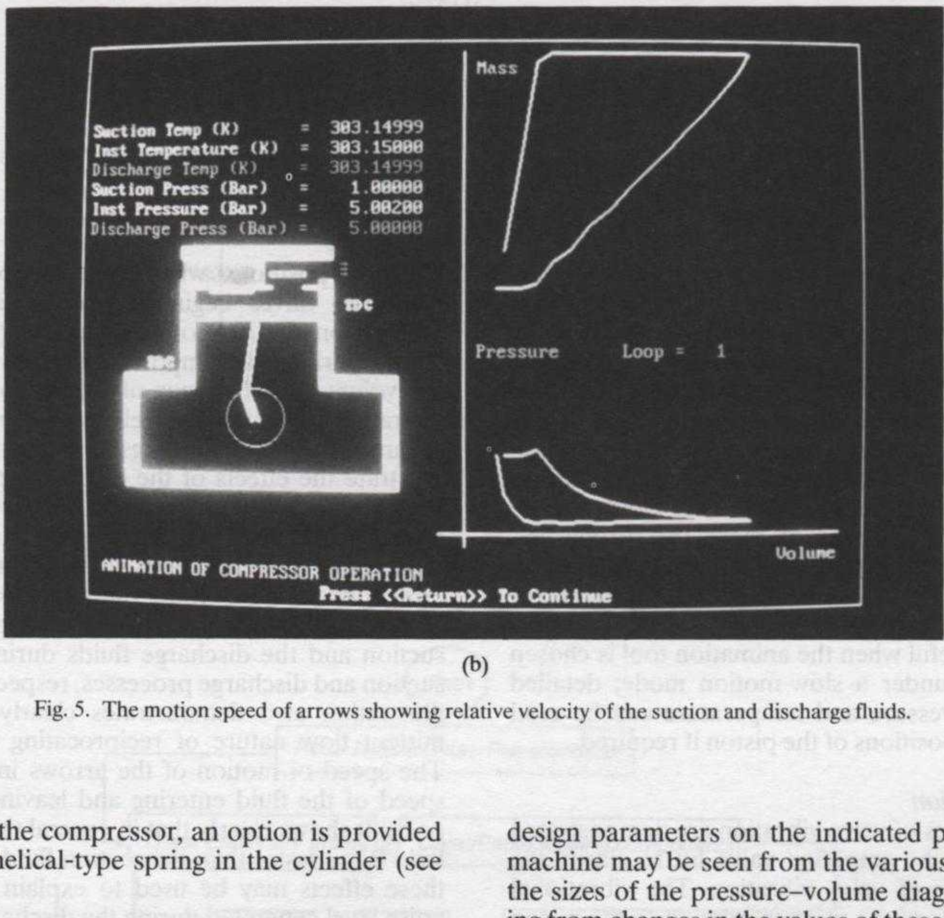
Piston positions where the suction and the discharge valves begin to open and close are marked on the side of the cylinder (see Fig. 4). These markings are important to show changes in the volumetric efficiency of the compressor with operating conditions as well as with other design parameters. These markings are also important to illustrate the effects of the discharge pressure on the volumetric efficiency. The mass–volume diagram will also assist in explaining the changes in the volumetric efficiency. Arrows indicating the flow directions of the working fluid are also added to show the direction and the relative speed of the suction and the discharge fluids during both the suction and discharge processes, respectively. This illustration also demonstrates clearly the intermittent flow nature of reciprocating machinery. The speed of motion of the arrows indicates the speed of the fluid entering and leaving the valve ports. It shows clearly that in general the discharge fluid flows faster than the suction fluid. Indirectly, these effects may be used to explain the higher noise level generated during the discharge process as compared to the suction process. These effects are shown for the suction process in Fig. 5(a) and for the discharge process in Fig. 5(b).

Compression/expansion effects

To provide a more realistic 'feel' for the compression and expansion effects that occur in the



(a)



(b)

Fig. 5. The motion speed of arrows showing relative velocity of the suction and discharge fluids.

cylinder of the compressor, an option is provided to place a helical-type spring in the cylinder (see Fig. 6).

Pressure–volume and mass–volume histories

As has been mentioned earlier, pressure–volume and mass–volume diagrams are shown simultaneously side by side with the animated schematic of the compressor. These two diagrams assist in showing the effects of various design parameters on the performance of the machine. The effects of the design parameters on the indicated power of the machine may be seen from the various shapes and the sizes of the pressure–volume diagrams resulting from changes in the values of these parameters. Comparisons of various mass–volume diagrams indicate how the capacity of the machine may be affected. When the animation tool executes in slow-motion mode, the effects of the design parameters on the resulting pressure–volume or mass–volume relationship may be immediately observed. Figure 7 shows the menu for the animation speed option.

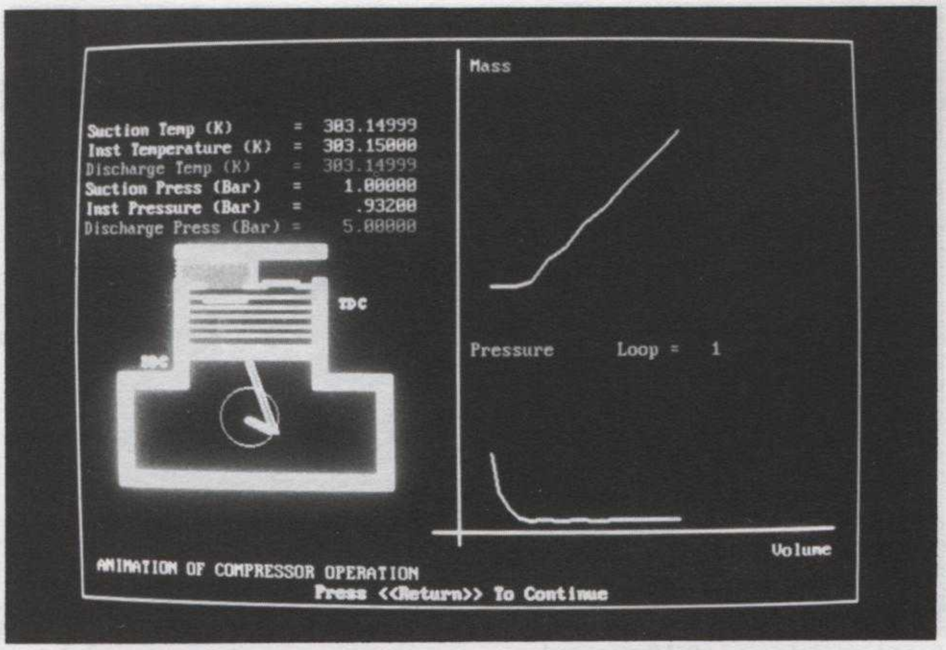


Fig. 6. An option is provided to place a helical spring in the cylinder to give a physical feel to the compression and the expansion processes.

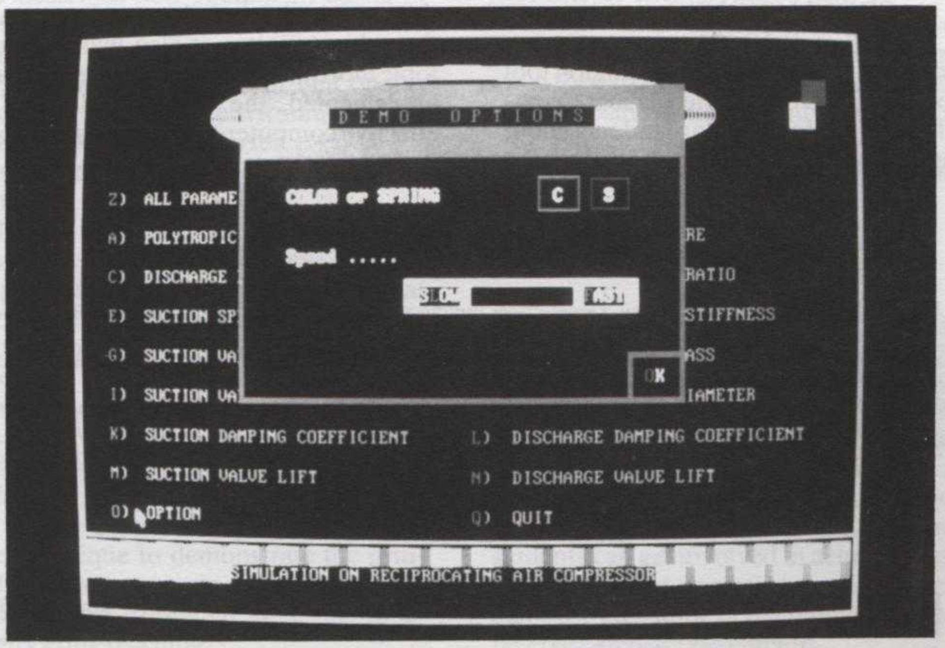


Fig. 7. Option menu for animation speed selection.

APPLICATIONS

In classroom teaching, only the post-processor is used. The simulated results of the effects of various design parameters are stored in the form of computer data files. These data are accessed by the post-processor for the animation. By using an overhead projector linked to the computer, the images displayed on the computer console can be viewed on the whiteboard of the classroom. Where such facilities are not available in the classroom, students are encouraged to access individually the animation tool, which is available in the campus computing room. They can then go through the animation and appreciate the subject matter at their own pace. Figure 8 shows the selection menu of the post-processor: once the option is clicked using the mouse or by pressing the highlighted character, the animation effects on that parameter will be shown.

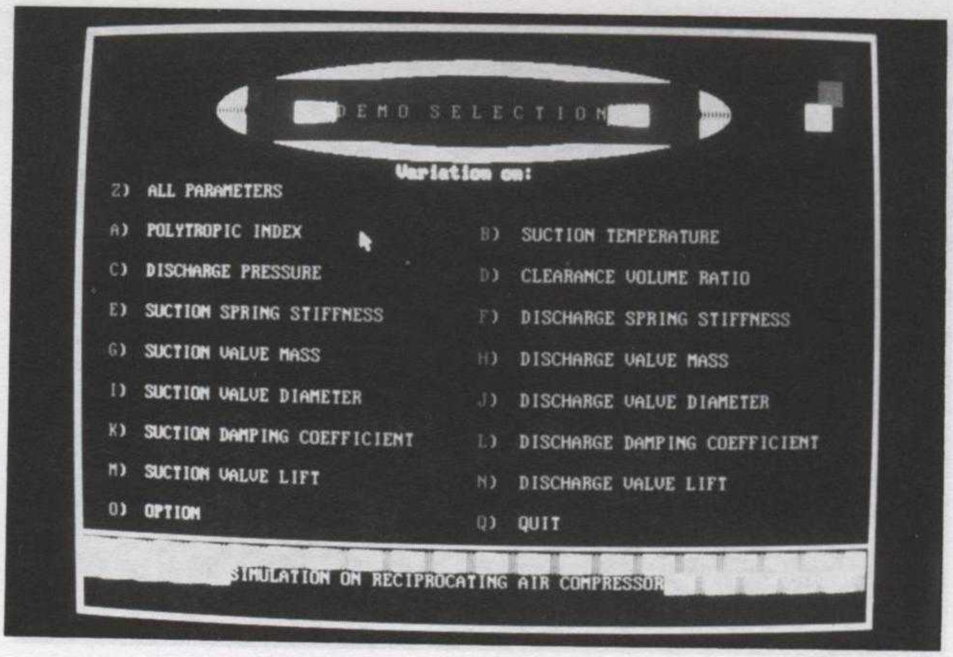


Fig. 8. User selection menu of the post-processor.

CONCLUSIONS

It has been found that a computer animation tool developed on an IBM-compatible personal computer is an effective aid for teaching students about reciprocating compressors. Besides shortening the time required for students to learn and appreciate the subject matter, it also makes learning of this topic more interesting. It is believed that if properly implemented, the tool can also be used as an effective computer-aided laboratory for the subject matter.

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