Computer-aided analysis of the Pelton wheel

F. MOUKALLED and **A. HONEIN**, Mechanical Engineering Department, Faculty of Engineering and Architecture, American University of Beirut, Beirut, Lebanon

Received 13th April 1994
Revised 11th October 1994

This paper describes PELTON, a microcomputer-based, interactive, and menu-driven software package for use as an educational tool by mechanical and civil engineering students in studying the operation of the Pelton wheel. The program is written in the Pascal computer language and runs on IBM PC, or compatible, computers. The package can handle problems related to impulse turbines by solving for unknown variables through a complete set of equations covering the turbine installation. Model-prototype problems can be tackled through similarity laws. This facility is included to help analysing and manipulating experimental data. Furthermore, the graphical utilities of PELTON allow the user to display diagrammatic sketches of the turbine, to employ some recommended charts, and to draw velocity triangles at several locations. The most important feature of the program, however, is its ability to plot the variation of any variable versus any other one. Through this option, the package guides the student in understanding the effects of varying design parameters on the overall performance of the machine. Finally, a comprehensive example problem is provided to show how user-friendly and encouraging-to-use PELTON is, and to demonstrate the capabilities of the package as an instructional tool.

NOMENCLATURE

D	twice the distance between the wheel centre and the jet centreline
D_j	jet diameter
D_p	pipe diameter
f	pipe friction loss coefficient
g	gravitational acceleration
h	net head
h''	energy head delivered to buckets
h_b	head loss on hydraulic friction and eddy losses over the buckets
h_d	kinetic energy head loss at discharge
h_n	head loss in the nozzle
h_p	head loss due to friction in the pipe
j	total number of jets
k	bucket friction coefficient
k_n	nozzle loss coefficient
L	pipe length

n_s	specific speed
Q	volume flow rate
r_1	radius of the wheel at which water enters
r_2	radius of the wheel at which water leaves
T	torque input to the shaft
u_1	axial wheel velocity at inlet
V_1	absolute velocity at inlet
V_2	absolute velocity at exit
x	r_2/r_1
Y	difference in elevation between headwater and nozzle.

Greek characters

α_1	angle between V_1 and the wheel velocity u_1
α_2	angle between V_2 and the wheel velocity u_2
β_2	bucket angle
γ	specific weight
ρ	density
ϕ	peripheral velocity factor

INTRODUCTION

The use of the computer in the educational field as an assisted way in instruction has proved to be very efficient, and instructional computer packages are gaining in importance nowadays. Very well prepared computer programs [1]–[5] play the role of a second instructor that can be relied on and referred to any time, and the student will consider them as an aid [1, 2] and not another load to carry or a complicated tool to use. In particular, the introduction of these packages into engineering programs has alleviated students from the lengthy computations required in solving complex processes. This in turn has led the student into a deeper understanding of the basic principles involved by allowing him/her to conduct more analysis of the problem than he/she would normally be able to do without a computer.

The Pelton wheel or the hydraulic impulse turbine is usually introduced to mechanical and civil engineering students in a second undergraduate fluid mechanics course where hydraulic machinery is thoroughly studied. Detailed description and analysis of the Pelton wheel can be found in most fluid mechanics textbooks (e.g. [6]–[9]). In addressing impulse turbine problems, beside computing velocities, losses and other variables, the main aim is to solve for and investigate conditions that maximize brake power or overall efficiency. Normally, students are informed of the effects of varying any parameter on the proceeding variables, but often to not have sufficient time to prove this for themselves, given the length of time required to calculate several examples by hand. With the wide spread of microcomputers, the majority of engineering students now have access to these machines and can use them to solve time-consuming problems. With this in mind, an interactive and menu-driven computer program was developed at the American University of Beirut to provide students with a tool that allows them to explore the effects of design changes on the performance of impulse turbines without the boredom of performing repeated hand calculations and/or the use of spreadsheets which is still very tedious as it requires development of all the governing equations and formatting of graphics.

The remainder of this paper first overviews the computer environment specification for the package, then follows with a description of the hydraulic impulse turbine and of the package utilities and special features. Finally, a comprehensive example problem is presented.

ENVIRONMENT SPECIFICATION

The program is written in the Pascal computer language using Turbo Pascal compiler version 6 [10, 11], that includes a powerful debugger and enhanced graphical utilities. The package runs on any IMB PC or compatible (PELTON was tested on 286, 386, 486 PCs, and under Microsoft windows), containing at least 640 kbytes of main memory, a Video or Enhanced Graphics Adapter card (VGA or EGA), and a colour monitor. A 1.2-Mbyte floppy disk is sufficient to install all required files.

The PC environment was chosen to provide an easy-to-use and cost-effective workstation; when the package is added with its user-friendly, menu-driven structure provides a powerful teaching aid.

THE HYDRAULIC IMPULSE TURBINE

A hydraulic impulse turbine (or a Pelton wheel) is one in which the pressure drop occurs in one or more stationary nozzles with no change in water pressure as it flows through the wheel buckets or vanes [6]–[9]. The kinetic energy of the water leaving the nozzle is transformed over the wheel into mechanical shaft work, fluid friction, mechanical dissipation, and kinetic energy at discharge.

An important parameter in analysing the Pelton wheel is the net head, h, available at the nozzle inlet. Applying Bernoulli's equation between headwater and nozzle entrance (Fig. 1) yields

$$Y = h + h_{\mathrm{p}} \tag{1}$$

where Y is the difference in elevation between headwater and the nozzle, and h_{p} is the pipe friction head loss. Applying the same equation between nozzle entrance and the location at discharge from the wheel (Fig. 1) gives

$$h = h_{\mathrm{n}} + h_{\mathrm{b}} + h_{\mathrm{d}} + h'' \tag{2}$$

where the meanings of the various terms in the above equation and the equations to follow are as given in the 'Nomenclature'. The energy $\gamma Q h''$ is transformed into work on the shaft and some mechanical losses (bearing friction and air resistance losses).

To maintain a constant speed of rotation, the flow rate may be varied with the load on the turbine. This is done by varying the jet diameter, D_{j}, through the needle nozzle. However, there is a unique D_{j}, which maximizes the power of the water leaving the nozzle. This diameter can be determined by developing an expression relating the jet power and the jet diameter using equations (1) and (2), differentiating with respect to D_{j}, and solving the resulting equation for the desired value of D_{j}. Algebraic manipulations yield

$$D_{\mathrm{j}} = \sqrt[4]{\frac{(1+k_{\mathrm{n}})D_{\mathrm{p}}^{5}}{2fL_{j}^{2}}} \tag{3}$$

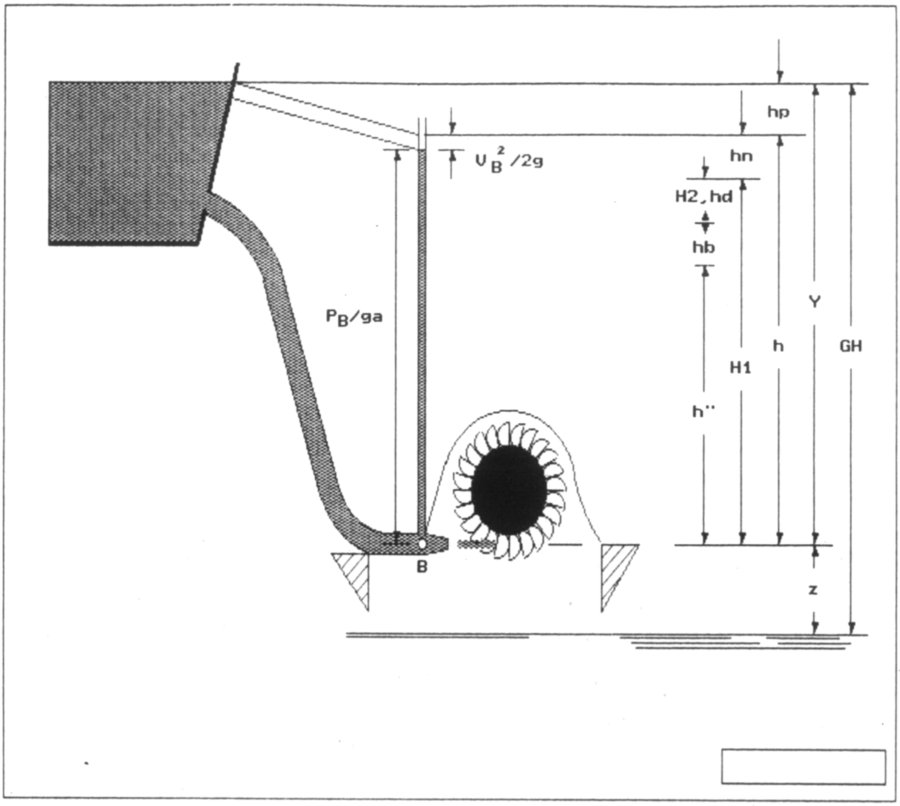


Fig. 1. Impulse turbine installation.

An equation for the torque on the shaft [6] of the turbine may be developed by applying the angular momentum equation over a control volume enclosing the wheel and is given by

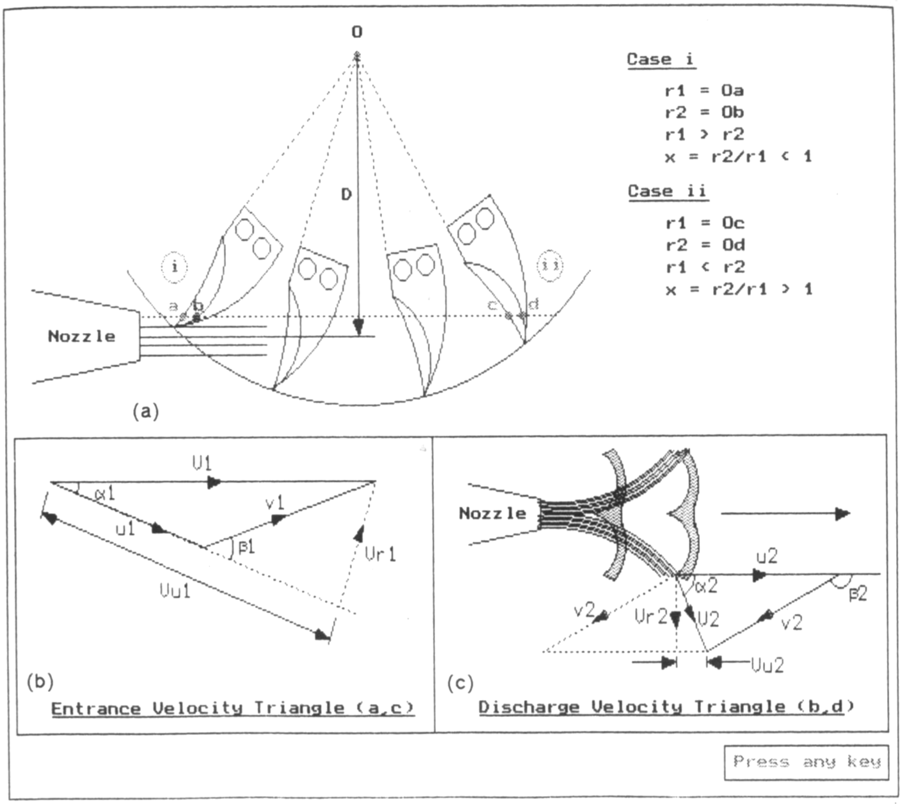
$$T = \rho Q(r_1 V_1 \cos\alpha_1 - r_2 V_2 \cos\alpha_2) \tag{4}$$

A combination of the above equation with an equation obtained from the velocity diagram at discharge (Fig. 2) and the Bernoulli equation between inlet to and exit from the bucket gives [6]:

$$T = \rho Q r_1 \left(V_1 \cos\alpha_1 - x^2 u_1 - \frac{x \cos\beta_2}{\sqrt{1+k}} \sqrt{V_1^2 + x^2 u_1^2 - 2u_1 V_1 \cos\alpha_1} \right) \tag{5}$$

Because the angle between V_1 and u_1 changes, depending on the position of the bucket when struck by the jet, an average value of α_1 is usually used in the above equation. Furthermore, using the torque equation (equation (4) or (5)), equations for the tangential force, hydraulic and overall efficiencies, output power, etc., can be derived but are not presented here, for compactness.

Finally, the specific speed of the impulse turbine [6] is defined as:



```
Case i

   r1  = Oa
   r2  = Ob
   r1  > r2
   x  = r2/r1  < 1

Case ii

   r1  = Oc
   r2  = Od
   r1  < r2
   x  = r2/r1  > 1
```

Fig. 2. (a) Water jet impinging on the buckjet of a Pelton wheel. (b) Entrance velocity triangle. (c) Discharge velocity triangle.

$$n_s = \frac{rpm_e \sqrt{bp}}{h^{5/4}} \tag{6}$$

where rpm_e is the rotative speed and bp is the brake power per jet. As given by equation (6), the specific speed is not a dimensionless quantity and is used in that form to be consistent with common practice, and users should be fully aware of this fact. For the Pelton wheel, the value of specific speed depends on the ratio D/D_j and in the SI system of units, best efficiencies for the machine are reached at an n_s value of about 17 $(N/m^{3/2}s^3)^{1/2}$.

DESCRIPTION OF THE PROGRAM

The program is divided into three major modules. The first one provides menus and data entry windows for variables and assumptions. These windows can also be used for separate data retrieval. A complete set of mostly used unit systems is available and the user can input and view variables in any system of units. The purpose of the second module is to solve for unknown variables in an iterative manner, using the appropriate set of equations. The role of the third module is to output results in tabular forms employing either the Imperial or the SI system of units. An additional important feature of the program is its ability to plot the variation, as a function of a chosen variable, of up to five quantities at a time. Finally, diagrams of the inlet and discharge bucket velocities can be drawn if the corresponding data is complete.

To increase the usefulness of the package and to facilitate its usage, other options and features are also included. The first option is a file handling utility used to save, open, print, and delete data files consisting of input and output data for problems. Using these options, easy correction of erroneous or missing data is permitted. Moreover, this facility allows the user to return variables to their initial values or the values before last calling the second module. Another feature of the program consists of one recommended chart [6] (Fig. 3) showing the variation of some variables with the specific speed. The user can retrieve values from the chart, and under her/his request, data can be used directly in solving problems requiring initial assumptions and guesses. Also included in the package are two diagrammatic sketches of the impulse turbine [6] (Figs. 1 and 2). These sketches help in visualizing some of the variables used in PELTON (dimensions, head losses, velocity triangles, etc.). Furthermore, the software is equipped with an *on-line* help, for all available options, to facilitate its use. Finally, errors in any input operation, errors that will stop the execution of

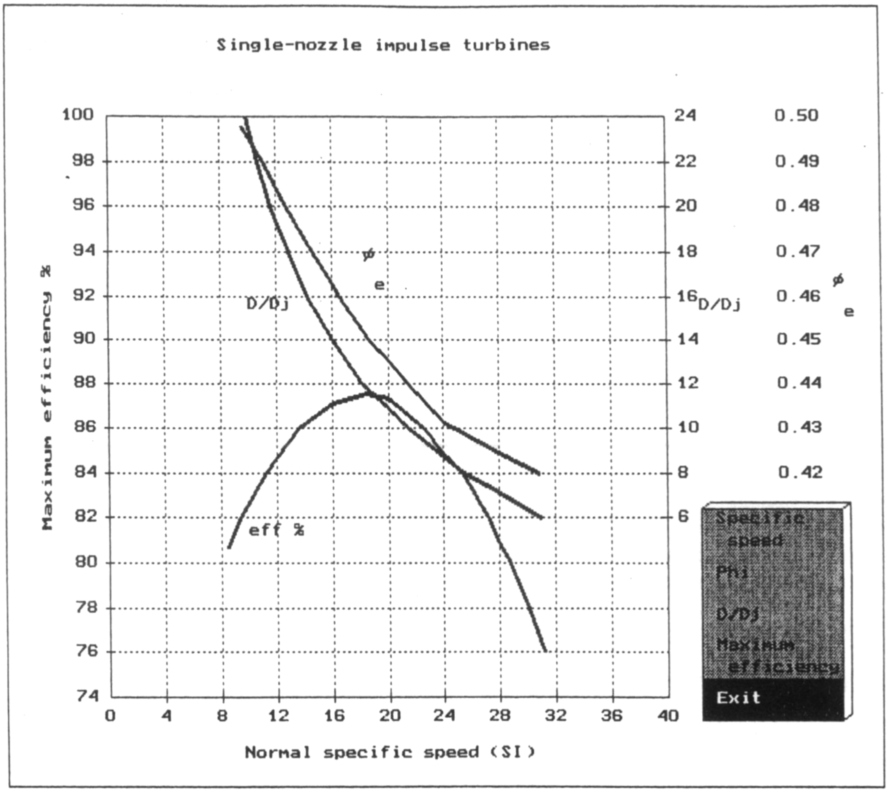


Fig. 3. Recommended design values of peripheral velocity factor, wheel to jet diameter ratio, and efficiency for Pelton wheels.

the program, and illegal input values for variables (negative dimension or loss factor greater than one) are carefully prevented.

The hierarchical structure of the software is shown in Fig. 4. The program is menu-driven and every interaction with the user is done in a user-friendly environment. The execution starts by typing PELTON at the DOS prompt, which causes the main menu to be displayed (Figs. 4 and 5) offering eight entries. By selecting the first entry (HELP), the user can access some information and instructions related to the package. The second entry (FILE) permits loading previously saved problems in addition to saving, printing, and deleting data files. To start a new problem, the INPUT entry should be chosen. Here the student may select sub-entry MODEL or PROTOTYPE. Having decided on a sub-entry, known variables may be entered to the program. As depicted in Fig. 5, the menu-driven structure of the package facilitates this task by guiding the user throughout the data entering procedure. Solution is then obtained by choosing the SOLVE entry. At this and the previous stage, data can be saved in a file that can be read at any later time. Results can be viewed using the OUTPUT or the INPUT entries and can be printed using the FILE entry.

The effect of varying one parameter on other parameters is obtained, as shown in Fig. 5, in the VARIATIONS entry. After specifying the input by the user (one input variable with its corresponding numerical range and a maximum of five output variables), the program subdivides the specified range into 50 equal increments and runs the second module to compute values at the ends of each sub-interval of the input variable and obtains arrays of output data that are displayed graphically. This facility allows a comprehensive analysis of the different parameters involved in the problem and permits the optimization of the machine performance. Through this option, the student may derive maximum educational benefits from the package. Instructors may assign homework problems to students, in which, they have to study the influence of a parameter on the turbine performance and to explain the generated results by relating the various variables through the equations governing the turbine installation. This helps students to understand the physics involved in the design and operation of the Pelton wheel. Furthermore, the recommended variation chart (Fig. 3) and the diagrammatic sketches (Figs. 1 and 2) can be accessed through the CHARTS and DRAWINGS entries respectively. Using also the last command, velocity diagrams can be drawn.

If the IBM 'graphics' module has been loaded at the beginning of the session, hard copies of figures displayed on the screen can be obtained using the 'Print Screen' command with a suitable printer.

EXAMPLE CALCULATIONS

To demonstrate the capabilities of PELTON, an example problem is presented, for which, the input and output data are listed in Table 1. In this problem, the first task is to solve for the jet diameter (D_j) which maximizes the power in the jet. The maximum jet power condition can be chosen from the assumptions and conditions menu in entry INPUT; however, to understand its effects on the parameters involved, variations of the jet velocity, discharge, net head, and jet power with the jet diameter are depicted in Fig. 6. These plots may be generated, depending on the speed of the PC used and the availability of a math-coprocessor, in at most one minute (a few seconds with an advanced computer). This is accomplished by choosing the VARIATIONS entry and then selecting the x and y variables. After selecting the range of variation of x and the unit system to be used, choosing the plot command instructs the program to subdivide the x interval into 50 sub-intervals and to solve the whole

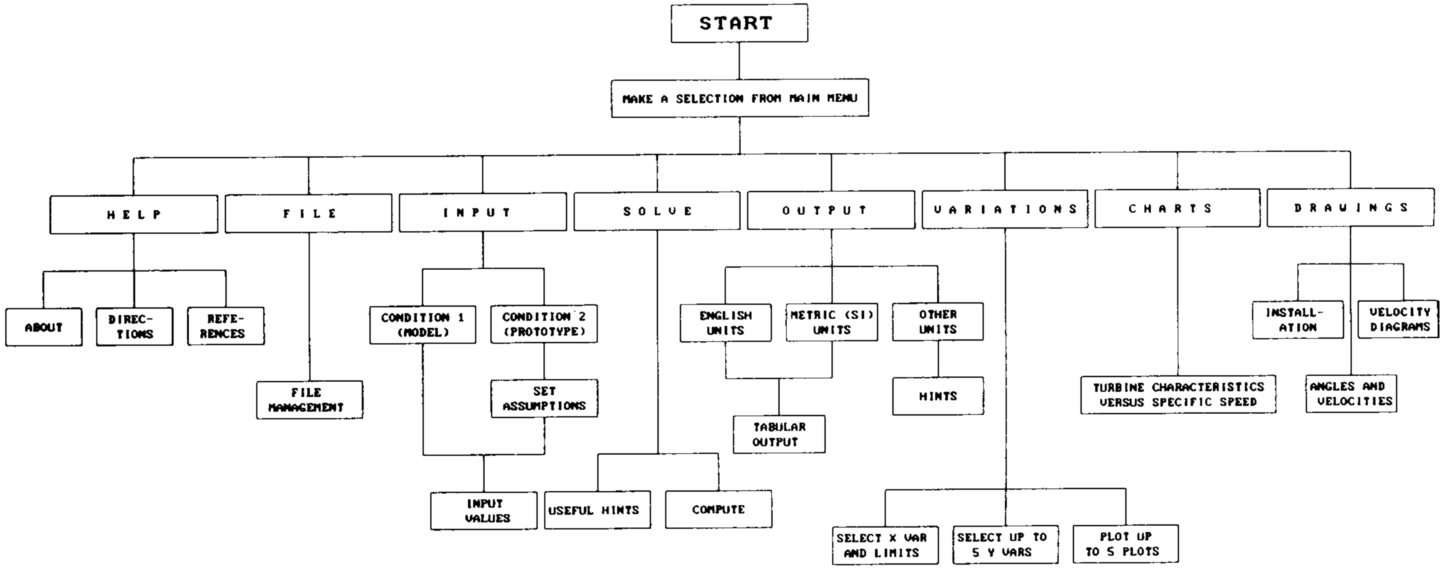


Fig. 4. Hierarchical menu structure of PELTON.

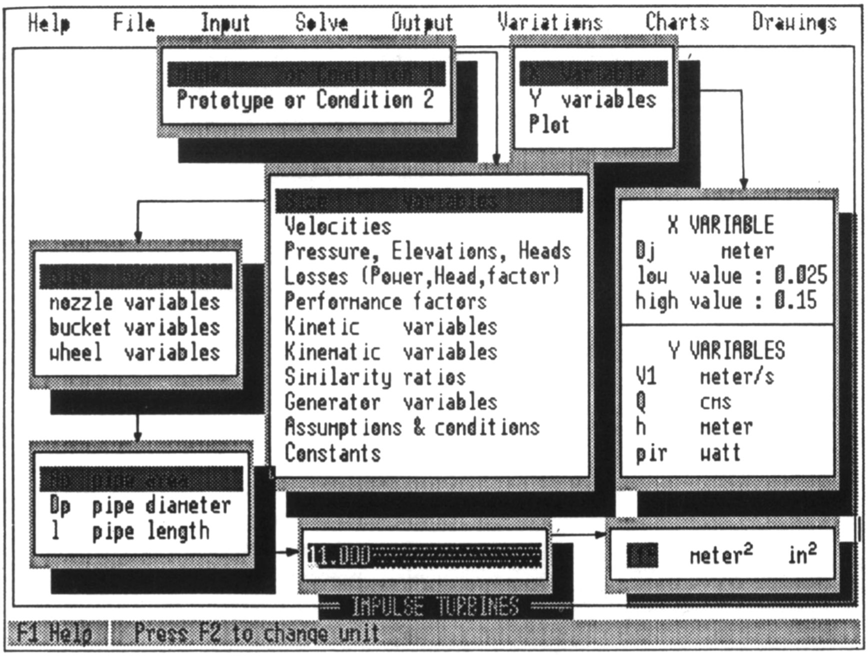


Fig. 5. Main menu and several illustrative sub-menus of PELTON.

Table 1. Input and output data for a Pelton wheel problem (output is in the SI system of units; angles in degrees and angular velocities in radian/s)

Input data—model or condition 1

Pipe variables

D_p pipe diameter: 0.150

L pipe length: 300.000

Nozzle variables

D_j jet diameter: 0.050

j # of jets/wheel: 1.000

n_j total # of jets: 1.000

Bucket variables

a_1 angle between V_1 & u_1: 15.000

b_2 angle between v_2 & u_2: 165.000

Wheel variables

D_w wheel diameter: 0.750

x r_2/r_1: 1.000

Pressure + elevations + heads

GH gross head: 150.000

z nozzle elevation: 90.000

Losses (power, head, factor)

f pipe friction factor: 0.020

x_n nozzle loss coefficient: 0.400

k bucket loss coefficient: 0.400

Performance factors

ϕ peripheral vel. factor at r_1: 0.500

Kinetic variables

T_s output shaft torque/jet: 420.000

Similarity ratios

RPM_1/RPM_2: 0.500

Assumptions & conditions

maximum jet power: NO

jet area $\ll$ pipe area: NO

Constants

g acc of gravity: 9.814

water density: 998.753

water specific weight: 9802.258

Table 1. Input and output data for a Pelton wheel problem (continued).

Output data—model or condition 1

Pipe variables

A_p	pipe area: 0.017

Nozzle variables

A_j	jet area> 0.002

Bucket variables

α_2	angle between V_2 & u_2: 54.278
β_1	angle between v_1 & u_1: 29.577

Wheel variables

r_1	wheel radius at entrance: 0.375
r_2	wheel radius at discharge: 0.375
D/D_j: 15.000	
N # of wheels: 1.000	

Entrance + outlet velocities

V_1	water or jet velocity: 27.710
v_1	Relat. inlet water velocity: 14.529
u_1	wheel (at r_1) velocity: 14.129
Vu_1	tang. inlet water velocity: 26.765
Vr_1	radial inlet water velocity: 7.171
V_2	water outlet velocity: 3.904
v_2	relat. outlet water velocity: 12.279
u_2	wheel (at r_2) velocity: 14.129
Vu_2	tang. outlet water velocity: 2.279
Vr_2	radial outlet water velocity: 3.178

Other velocity variables

C_1	V_1 velocity coefficient (C_v): 0.980
C_2	V_2 velocity coefficient: 0.138
w	rotative velocity: 37.678
RPM	: 359.802
V_p	pipe velocity: 3.078

Pressure + elevations + heads

PB	pipe end pressure: 394206.545
H_1	wheel inlet vel. head: 39.117
y	static head: 60.000

Losses (power, head, factor)

h_p	pipe loss: 19.317
h_n	nozzle loss: 1.564
h_b	bucket loss: 3.072
h_d	discharge loss (H_2): 0.793
pl_n	nozzle power loss: 834.111
pl_b	bucket power loss: 1638. 106

Losses (power, head, factor) continued

pl_d	discharge power loss: 422.984
pl_{nt}	total nozzle power loss: 834.111
pmf	mechanical power loss: 2974.193

Performance factors

n_s	specific speed: 13.930
n_n	nozzle efficiency: 0.961
n_h	hydraulic efficiency: 0.866
n_m	mechanical efficiency: 0.841
n_o	overall efficiency: 0.729

Kinetic variables

pw	water power at pipe end: 21686.906
pir	jet power input to wheel: 20852.794
pj_t	total jets power: 20852.794
pis	power input to shaft/jet: 18791.703
pb	brake power/jet: 15817.509
pb_w	brake power/wheel: 15817.509
pb_t	total brake power: 15817.509
T	torque input to shaft/jet: 498.973
T_f	friction torque/jet: 78.973
T_{sw}	output shaft torque/wheel: 420.000
T_{st}	total output torque: 420.000
F	force on wheel/jet: 1300.595

Kinematic variables

Q	discharge per jet: 0.054
Q_t	total discharge: 0.054
h	net head: 40.682
h''	head extracted from water: 35.251

Similarity ratios

D_1/D_2 : 1.000

h_1/h_2 : 0.250

Q_1/Q_2 per jet: 0.500

T_1/T_2 torque input to shaft/jet: 0.250

pis_1/pis_2 power input to shaft/jet: 0.125

Ts_1/TS_2 output shaft torque/jet: 0.222

pb_1/pb_2 brake power/jet: 0.111

Similarity conditions

homologous conditions: YES

same efficiency: NO

same turbine: YES

Table 1. Input and output data for a Pelton wheel problem (continued).

Input data—prototype or condition 2

Nozzle variables

j	# of jets/wheel: 1.000

Wheel variables

x	r_2/r_1: 1.000
N	# of wheels: 1.000

Losses (power, head, factor)

pmf	mechanical power loss: 8198.839

Output data—prototype or condition 2

Nozzle variables

A_j	jet area: 0.002
D_j	jet diameter: 0.050
n_j	total # of jets: 1.000

Wheel variables

D_w	wheel diameter: 0.750
r_1	wheel radius at entrance: 0.375
r_2	wheel radius at discharge: 0.375
D/D_j	: 14.998

Entrance + outlet velocities

V_1	water or jet velocity: 55.406
u_1	wheel (at r_1) velocity: 28.258
u_2	wheel (at r_2) velocity: 28.258

Other velocity variables

C_1	V_1 velocity coefficient (C_v): 0.980
w	rotative velocity: 75.356
RPM	: 719.605

Presure + elevations + heads

H_1	wheel inlet velocity head: 156. 396

Losses (power, head, factor)

h_n	nozzle loss: 6.334
pl_n	nozzle power loss: 6753.058
pl_{nt}	total nozzle power loss: 6753.058
x_n	nozzle loss coefficient: 0.040

Performance factors

n_s	specific speed: 14.764
n_n	nozzle efficiency: 0.961
n_h	hydraulic efficiency: 0.866
n_m	mechanical efficiency: 0.945
n_o	overall efficiency: 0.819
ϕ	peripheral vel. factor at r_1: 0.500

Kinetic variables

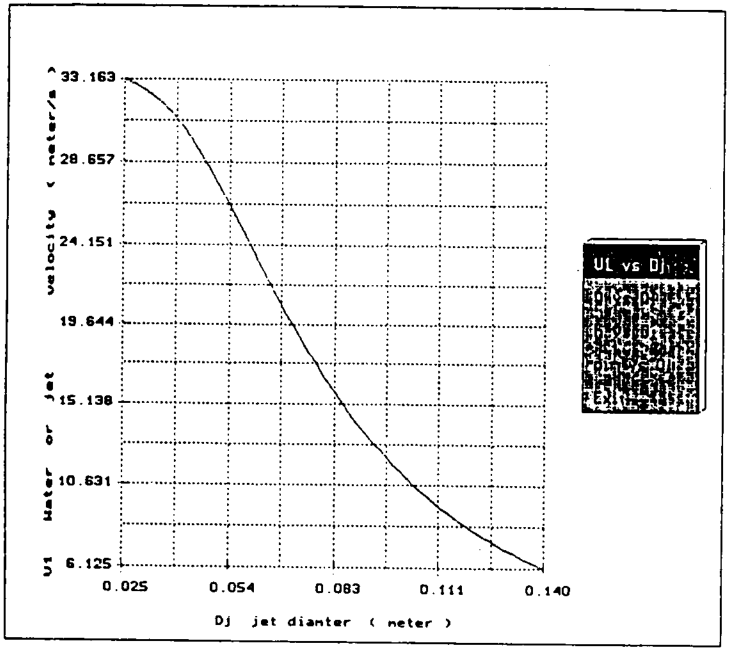
pw	water power at pipe end: 173495.251
pir	jet power input to wheel: 166742.193
pj_t	total jet power: 166742.193
pis	power input to shaft/jet: 150333.626
pb	brake power/jet: 142134.787
pb_w	brake power/wheel: 142134.787
pb_t	total brake power: 142134.787
T	torque input to shaft/jet: 1995.893
T_f	friction torque/jet: 108.851
T_s	output shaft torque/jet: 1887.042
T_{sw}	output shaft torque/wheel: 1887.042
T_{st}	total output torque: 1887.042

Kinematic variables

Q	discharge per jet: 0.108
Q_t	total discharge: 0.108
h	net head: 162.730
h''	head extracted from water: 141.005

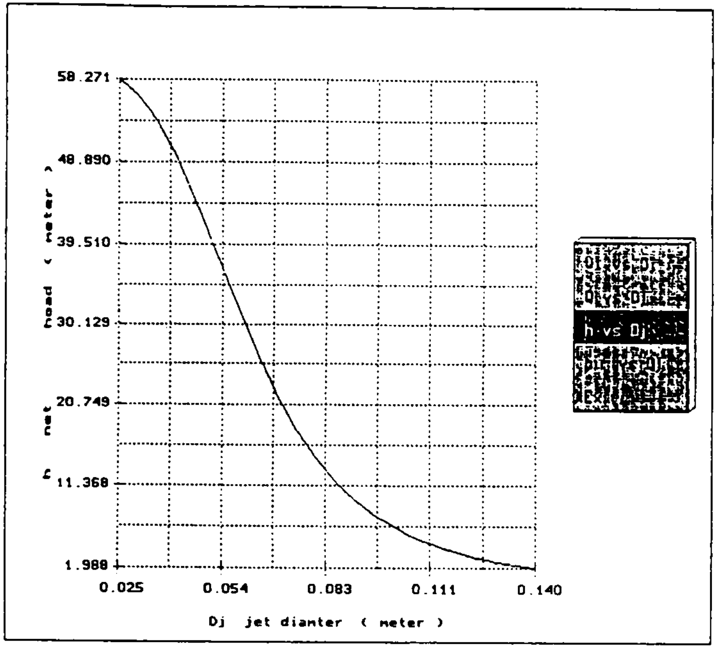
problem 50 times in order to compute and store y values in arrays to be displayed graphically. As shown in Fig. 6(a) and (b), the jet velocity and the net head in the jet decrease with increasing jet diameter while the volume flow rate increases (Fig. 6(c)). To explain this behaviour, the following energy equation written between head water and jet exit should be considered:

$$\begin{aligned}\text{gross head } (Y) = {} & \text{friction in the pipe } (K_1 D_j^4 V_j^2) \\ & + \text{friction in the nozzle } (K_2 V_j^2) \\ & + \text{head in the jet} \end{aligned} \tag{7}$$



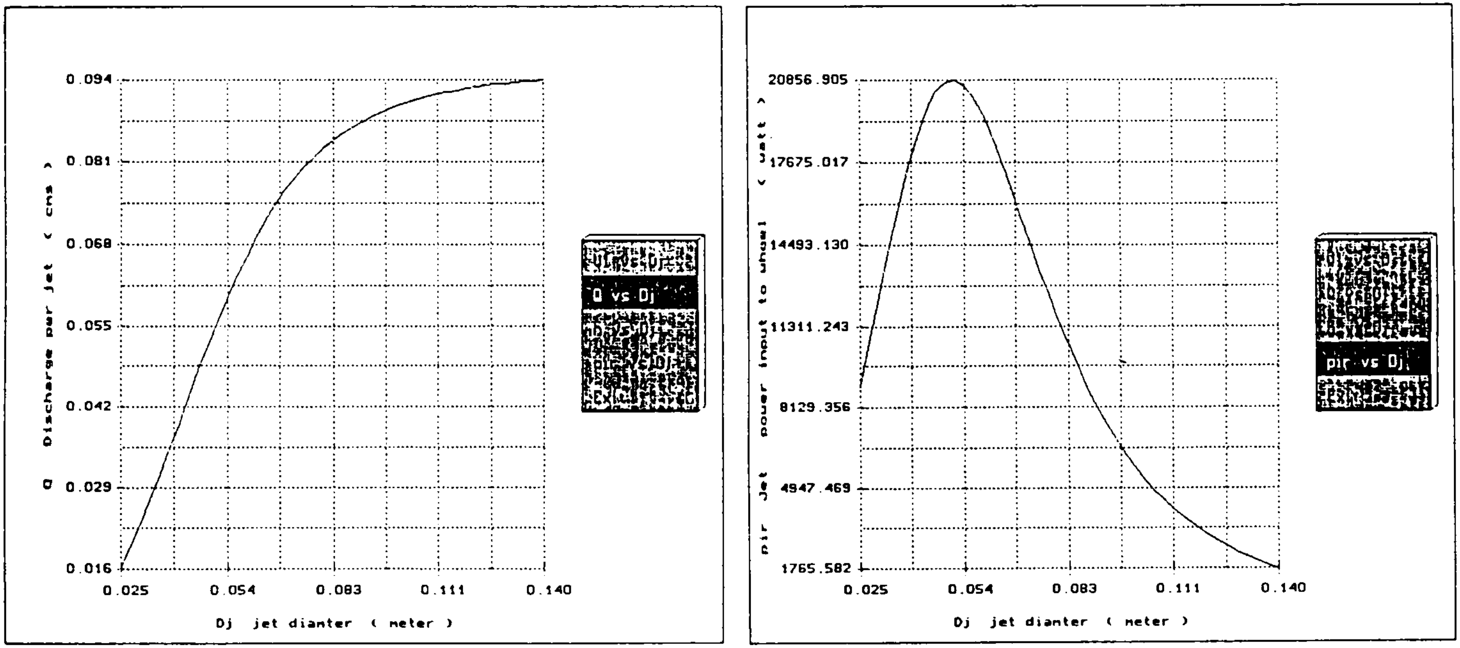
Ul Water or jet velocity (meter/s)
33.163
28.657
24.151
19.644
15.138
10.631
6.125
0.025
0.054
0.083
0.111
0.140
Dj jet dianter (meter)
Ul vs Dj

(a)



h net head (meter)
58.271
48.890
39.510
30.129
20.749
11.368
1.988
0.025
0.054
0.083
0.111
0.140
Dj jet dianter (meter)
h vs Dj

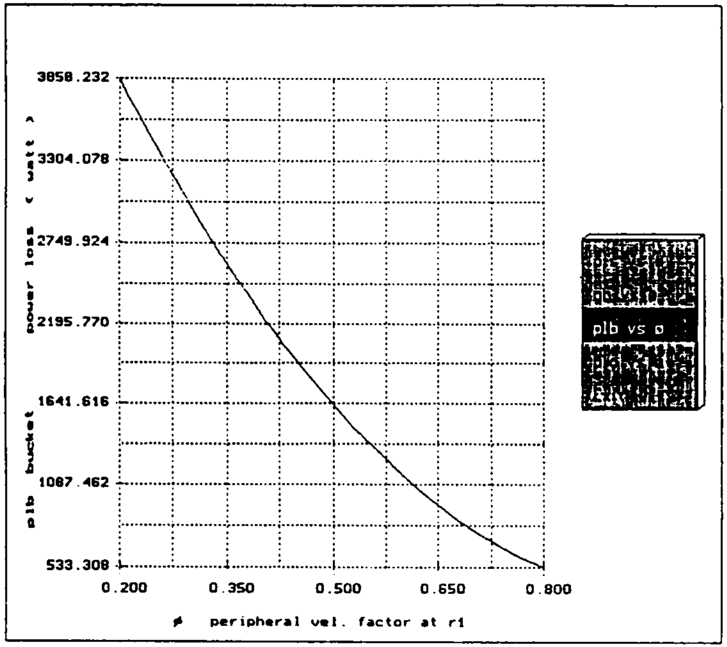
(b)



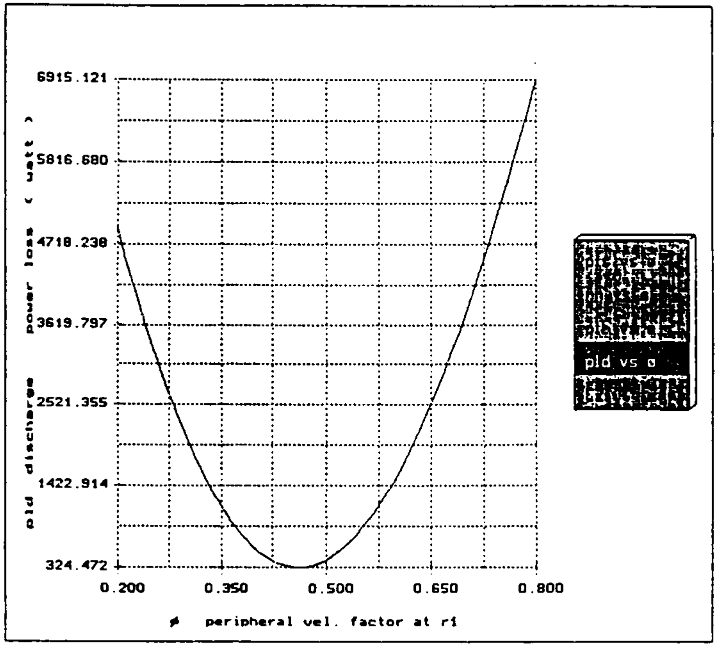
(c)

(d)

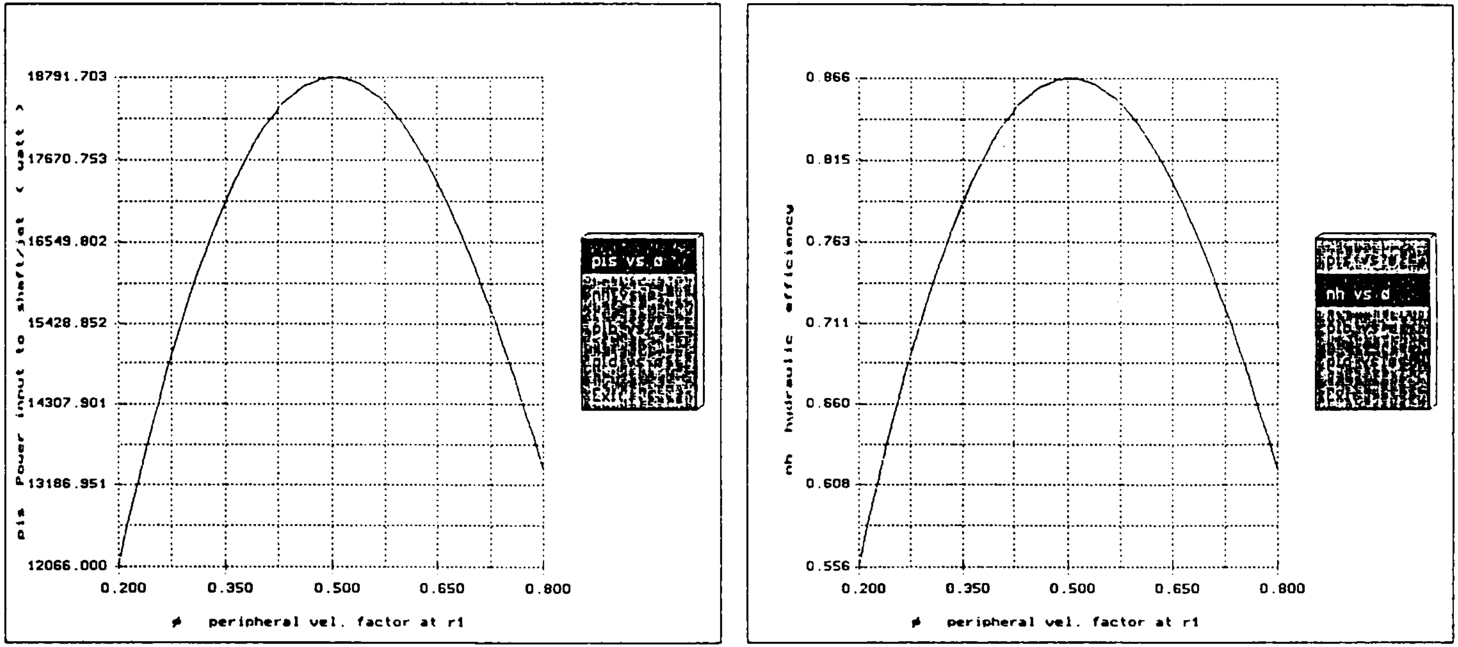
Fig. 6. Variation of (a) jet velocity with jet diameter, (b) net head with jet diameter, (c) volume flow rate with jet diameter, and (d) jet power with jet diameter (test problem).


3858.232
3304.078
2749.924
2195.770
1641.616
1087.462
533.308
plb bucket power loss (watt)
0.200
0.350
0.500
0.650
0.800
ø peripheral vel. factor at r1
plb vs ø

(a)


6915.121
5816.680
4718.238
3619.797
2521.355
1422.914
324.472
pld discharge power loss (watt)
0.200
0.350
0.500
0.650
0.800
ø peripheral vel. factor at r1
pld vs ø

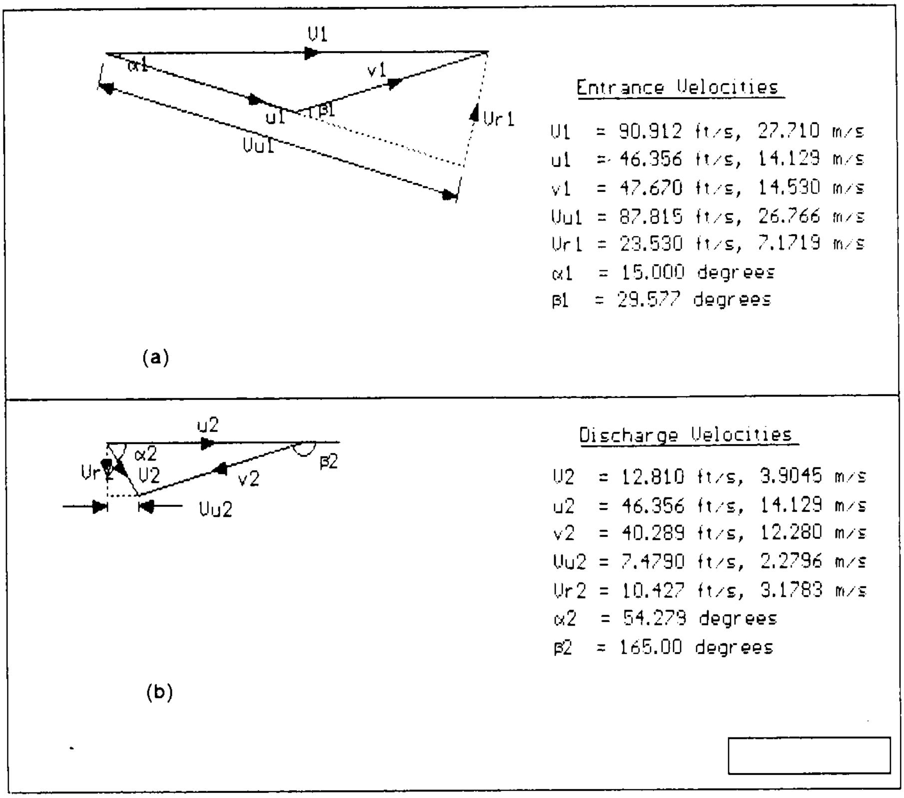
(b)



(c)

(d)

Fig. 7. Variation of (a) friction power loss over the buckets with the peripheral velocity factor, (b) discharge power loss with the peripheral velocity factory, (c) power input to shaft with the peripheral velocity factor, and (d) turbine hydraulic efficiency with the peripheral velocity factor (test problem).



```
Entrance Velocities

V1  = 90.912 ft/s, 27.710 m/s
u1  = 46.356 ft/s, 14.129 m/s
v1  = 47.670 ft/s, 14.530 m/s
Vu1 = 87.815 ft/s, 26.766 m/s
Vr1 = 23.530 ft/s, 7.1719 m/s
α1  = 15.000 degrees
β1  = 29.577 degrees

Discharge Velocities

V2  = 12.810 ft/s, 3.9045 m/s
u2  = 46.356 ft/s, 14.129 m/s
v2  = 40.289 ft/s, 12.280 m/s
Vu2 = 7.4790 ft/s, 2.2796 m/s
Vr2 = 10.427 ft/s, 3.1783 m/s
α2  = 54.279 degrees
β2  = 165.00 degrees
```

Fig. 8. Velocity diagram (a) at inlet to the bucket of the Pelton wheel, and (b) at exit from the bucket of the Pelton wheel (test problem).

Since the gross head is constant, equation (7) shows that the jet velocity should decrease with increasing jet diameter. Moreover, because the net head (or head in the jet) is proportional to the square of the jet velocity $(h = (1/C_v)^2\, V^2/2g)$ it should decrease with increasing values of the jet diameter. Furthermore, the decrease in the net head is associated with an increase in losses in the pipe. Since friction in the pipe is proportional to the square of the pipe's average velocity, the latter should increase along with the volume flow rate. Then, it should be apparent from the preceding discussion that, as the size of the nozzle increases, the discharge increases while the jet velocity decreases; consequently, there should be an intermediate size which maximizes the jet power (Fig. 6(d)).

Having calculated the optimum jet diameter (5 cm, Fig. 6(d)), the next step is to find the value of the peripheral velocity factor which maximizes the hydraulic efficiency of the turbine. For this purpose, the variation of the bucket power loss, discharge power loss, power input to shaft, and hydraulic efficiency with the peripheral velocity factor are presented in Figs 7(a) to (d), respectively. The power loss over the buckets being proportional to the square of the relative velocity of the flowing fluid, decreases (Fig. 7(a)) with increasing values of $\phi(\phi = u/(2gh)^{1/2})$ due to a decrease in v_1 (i.e. V_1 is constant and u is increasing).

Furthermore, the velocity diagram (Fig. 2(c)) shows that the value of V_2 decreases as the wheel speed increases until it reaches a minimum value and then increases again. Hence, at some intermediate speed, the kinetic energy lost at discharge from the buckets is a minimum (Fig. 7(b)). Therefore, the power input to shaft (Fig. 7(c)) and the hydraulic efficiency (Fig. 7(d)) will reach a maximum value when the sum of these two losses is minimum. This occurs at an optimal peripheral velocity factor value of 0.5 (Figs 7(c) and (d)).

Using the computed values of 5 cm and 0.5 for the jet diameter and the peripheral velocity factor, the problem is solved and the values of the various quantities involved are computed and displayed in Table 1. The velocity triangles at entrance and discharge from the buckets are displayed in Figs 8(a) and (b), respectively. Finally, the speed of the wheel is doubled and, invoking similarity laws, the performance of the wheel under the new conditions is easily determined by PELTON (Table 1). This option is added to enable predicting the performance of a Pelton wheel for conditions different than those under which it was tested, when detailed data are not available.

CONCLUSION

A microcomputer-based program for the analysis of the Pelton wheel was developed. The menu structure of the program along with its help and graphical capabilities provide an efficient educational tool for the mechanical and civil engineering student and allow her/him to explore the field of impulse turbines more easily. The example problem presented showed the educational benefits of the package. Finally, copies of the package will be provided to users upon request addressed to the first-named author.

ACKNOWLEDGEMENT

The financial support provided by the University Research Board of the American University of Beirut through Grant No. 48816 is gratefully acknowledged.

REFERENCES

[1] Diab, H., Tabbara, H., Moukalled, F., Kaysi, I., and Raad, L., 'GEOCAD: an educational tool for flexible pavement design and maintenance', *International Journal of Applied Engineering Education*, 7(4), 307–315 (1991).

[2] Moukalled, F., and Lakkis, I., 'Computer-aided analysis of gas turbine cycles', *International Journal of Mechanical Engineering Education*, **22** (3), 209–227 (1994).

[3] Moukalled, F., Naim, N., and Lakkis, I., 'Computer-aided analysis of centrifugal compressors', *International Journal of Mechanical Engineering Education*, **22** (4), 245–258 (1994).

[4] Evans, R. L., and Mawle, C., 'Microcomputer-based analysis of steam power plants', *International Journal of Mechanical Engineering Education*, **17**(3), 217–230 (1989).

[5] Brychcy, M. L., and Taulbe, D. B., 'Calculation and graphics display of airfoil and wing characteristics', *International Journal of Mechanical Engineering Education*, **18**(3), 157–168 (1990).

[6] Daugherty, R. L., Franzini, J. B., and Finnemore, E. J., *Fluid Mechanics with Engineering Applications*, McGraw-Hill, Singapore, 1989.

[7] Streeter, V. L., and Wylie, E. B., *Fluid Mechanics*, 7th edn, McGraw-Hill, Tokyo, 1979.

[8] Massey, B. S., *Mechanics of Fluids*, 4th edn, Van Nostrand Reinhold, London, 1979.

[9] Nagaratnam, S., *Fluid Mechanics and Systems*, Tata McGraw-Hill, Bombay, 1971.

[10] *Turbo Pascal Owner's Handbook*, Borland International, Scotts Valley, CA, 1989.

[11] Stephan O'Brian, *Turbo Pascal 6, The Complete Reference*, Borland-Osborne/McGraw-Hill, U.S.A. 1991.