2006-1991: A VIRTUAL LABORATORY ON FLUID MECHANICS

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A Virtual Laboratory on Fluid Mechanics

Abstract

This paper describes the development of an interactive Web-based virtual laboratory on fluid mechanics at Stevens Institute of Technology (SIT),[1] which integrates animations, graphics and analysis results in order to achieve a realistic feel of the experiment and to enhance the students' understanding of some complex concepts of fluid mechanics. Based on existing real experimental setups, different experiment simulations were implemented using the Python programming language, such as a wind tunnel and an air flow rig. In the wind tunnel experiment, the lift forces for several kinds of airfoils can be experimented with virtually. The users can specify certain parameters for controlling the simulations and obtain the corresponding lift force outputs, including tables, figures and data listings. Furthermore, the users can display a 3-D rendering of the wind tunnel equipment in the graphical user interface as well as a 2-D animation of the stream lines. The simulation achieves a good degree of accuracy for steady state conditions over a wide range of parameters.

Key words: Virtual laboratory, fluid mechanics, wind tunnel, air flow rig, Python programming language

Introduction

Fluid mechanics is the study of fluids, i.e. gases and liquids. It is one of the most challenging areas of engineering sciences with difficult to understand concepts. Many kinds of experimental equipment are used to study the various phenomena of fluid mechanics, such as wind tunnels, Reynolds number rigs and fluid flow rigs. While such equipment is very helpful to students for better understanding theoretical concepts through experimentation, it is also difficult to analyze arbitrary fluid motion. Currently, modern information technology based on the Internet is rapidly being adopted in engineering education as a tool for enhancing the educational experience of students residing on campus as well as beyond the local campus. Many educational instructors have implemented virtual and remote laboratories.[2,3,4,5] Chaturvedi et al.[6] developed a thermo-fluids laboratory titled "Venturimeter as a Flow Measuring Device" as a computer-based experiment for undergraduates. This virtual experiment combines three unique aspects: the use of computer-generated data to recreate the physical phenomenon, virtual experimentation and measurements on a computer, and the coupling of the virtual experiment with the LabVIEW software to introduce students to digital data acquisition and analysis. Gillet et al.[7] described the development and sharing of Web-based experimentation resources. Their program integrates the necessary components to carry out hands-on practice in a flexible learning context. At the same time, the experimental devices of this program can be accessed by more students from remote locations at any time over the Internet. A physical laboratory called SoftLab was developed at Purdue University[8] to provide an environment for both physical experiments and numerical simulations. A more realistic Fluids Laboratory[9] as an integrated learning environment was developed by IIHR-Hydroscience & Engineering at The University of Iowa. This laboratory is configured to provide unrestricted and user-friendly access to comprehensive insights in fluid mechanics and hydraulics. With the addition of the Virtual Fluids Lab, experiments can be conducted online at any time and from any place.

This paper describes the development of several virtual laboratories at SIT, including a wind tunnel and an air/oil flow rig. In the wind tunnel experiment, the lift forces for several kinds of airfoils, for instance a plain-flap airfoil and a slotted-flap airfoil, can be experimented with virtually. The students can specify certain parameters for controlling the simulations and obtain the corresponding lift force outputs, including tables, figures and data listings. Furthermore, the students can display a 3-D rendering of the wind tunnel equipment as well as a 2-D animation of the stream lines in the graphical user interface. In the virtual flow rig, the air/oil flow through a pipe is being modeled. An entrance region with a nearly inviscid upstream is modeled, followed by retardation of the axial flow at the wall and consequently acceleration of the center core flow to satisfy the incompressible continuity requirement. At a finite distance from the pipe entrance, the boundary layers merge and the inviscid core disappears[10].

Architecture of Virtual Fluid Laboratory

As a virtual part of the remote laboratory system at SIT,[11,12,13,14] the virtual laboratory is developed to complement the existing remotely operated experiments. Many students are enabled to perform the experimental simulations simultaneously through the Internet from any place at any time. Figure 1 shows the general structure of the remote laboratory, including the real and virtual experiments. The real wind tunnel can be operated remotely through the Internet. At the same time, the students can perform the dynamic and interactive virtual experiment over Internet. The virtual laboratories are implemented using the OpenGL Python programming language. Python is an interpreted, interactive, object-oriented programming language[15,16,17,18] offering very high level dynamic data types.

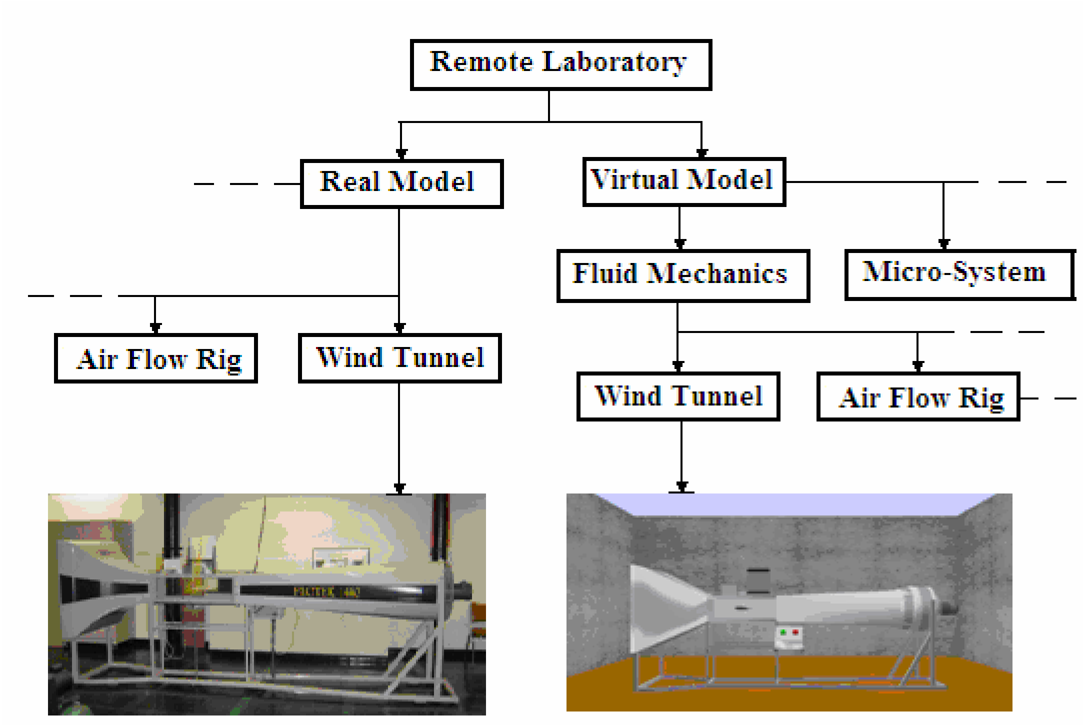
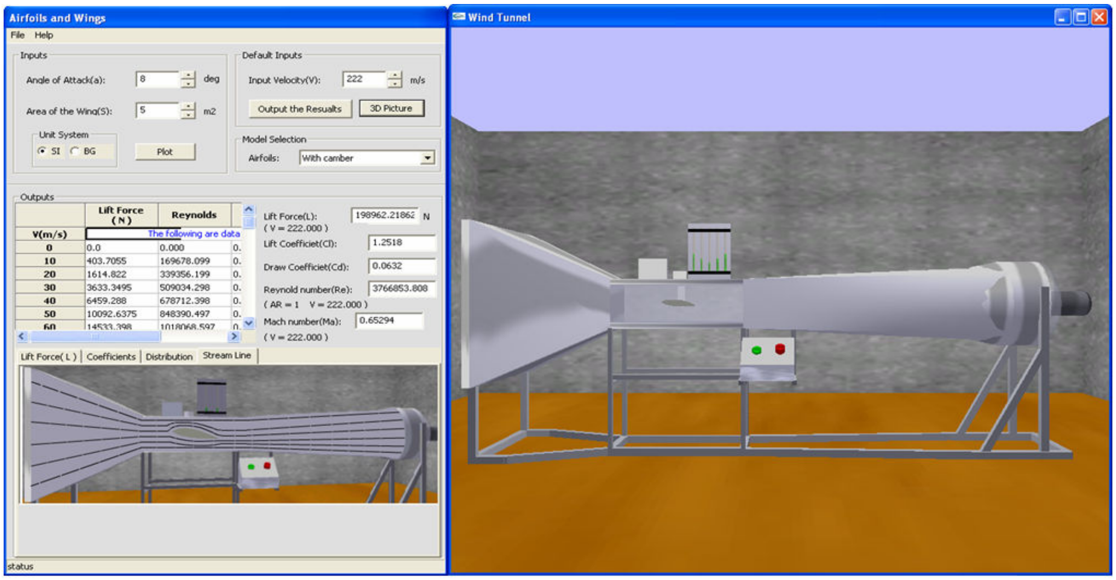


Figure 1: Remote laboratory structure

Virtual Wind Tunnel Laboratory

The wind tunnel can be used to conduct experiments on airfoils as well as on various bodies. Generally, the main experimental result for an airfoil is the lift force while for other bodies it is the drag force. Because the airfoils and bodies are quite different in their properties and associated models, we are designing separate virtual laboratories for airfoils and bodies.

Airfoil Wind Tunnel: Figure 2 depicts the graphical user interface of the virtual wind tunnel with an airfoil. The lift forces for several kinds of airfoils can be determined. The students can display a 3-D rendering of the wind tunnel and a 2-D animation of the stream lines. The lift forces are output in the form of an output table, an output graph or output data.



Angle of Attack(a): 8 deg

Area of the Wing(S): 5 m2

Unit System: ● SI ○ BG

Input Velocity(V): 222 m/s

Airfoils: With camber

	Lift Force (N)	Reynolds	
V(m/s)		The following are data	
0	0.0	0.000	0.
10	403.7055	169678.099	0.
20	1614.822	339356.199	0.
30	3633.3495	509034.298	0.
40	6459.288	678712.398	0.
50	10092.6375	848390.497	0.
60	14533.398	1018068.597	0.

Lift Force(L): 198962.21862 N
(V = 222.000)

Lift Coefficiet(Cl): 1.2518

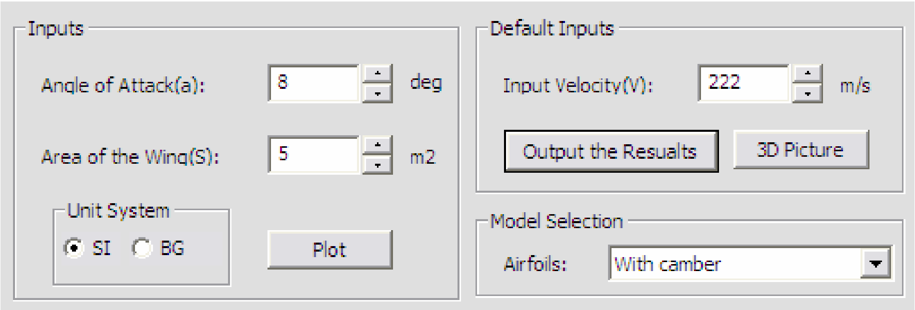
Draw Coefficiet(Cd): 0.0632

Reynold number(Re): 3766853.808
(AR = 1 V = 222.000)

Mach number(Ma): 0.65294
(V = 222.000)

Figure 2: Virtual wind tunnel laboratory with airfoil

The students are enabled to select the input parameters (angle of attack, area of airfoil), select the system of units and request the corresponding results by clicking the “Plot” button as shown in Figure 3. If the students want to get the outputs for a specific velocity, they can input it in the Default Inputs block and then click the “Output the Results” button. For example, if the angle of attack is 8°, the area of the airfoil is 5 m^2 and the specified velocity is 222 m/s, the students obtain the outputs shown in Figure 4.



Angle of Attack(a): 8 deg

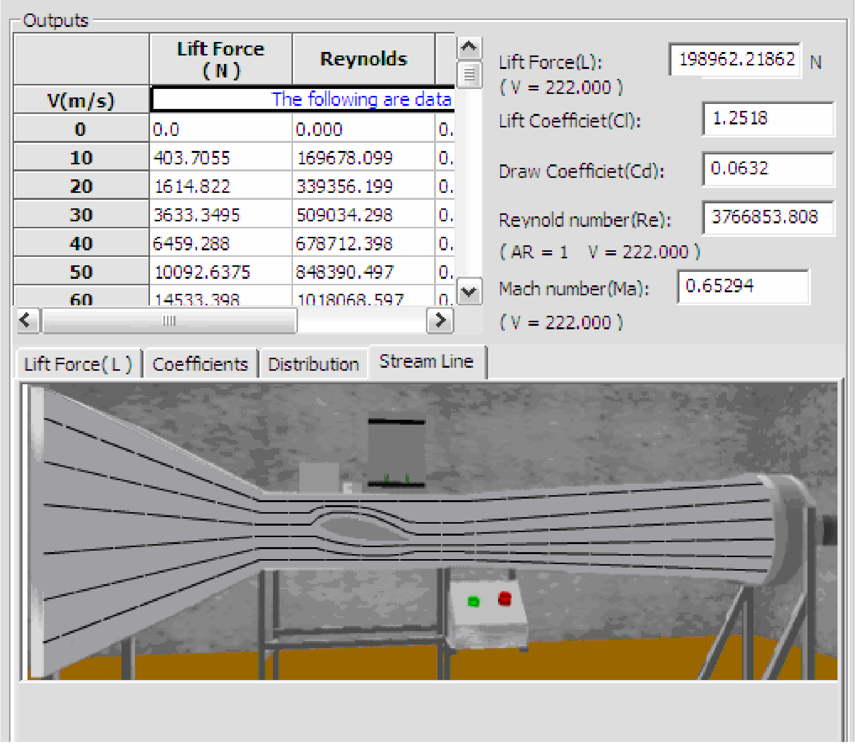
Area of the Wing(S): 5 m2

Unit System: ● SI ○ BG

Input Velocity(V): 222 m/s

Airfoils: With camber

Figure 3: Input panel of virtual wind tunnel laboratory



	Lift Force (N)	Reynolds	
V(m/s)	The following are data		
0	0.0	0.000	0.
10	403.7055	169678.099	0.
20	1614.822	339356.199	0.
30	3633.3495	509034.298	0.
40	6459.288	678712.398	0.
50	10092.6375	848390.497	0.
60	14533.398	1018068.597	0.

Lift Force(L): 198962.21862 N
(V = 222.000)
Lift Coefficiet(Cl): 1.2518
Draw Coefficiet(Cd): 0.0632
Reynold number(Re): 3766853.808
(AR = 1 V = 222.000)
Mach number(Ma): 0.65294
(V = 222.000)

Figure 4: Output panel of virtual wind tunnel laboratory

Figure 5 shows the selection panel for choosing an airfoil from the available airfoil models. Upon selection of a specific airfoil, all outputs including lift forces, lift coefficients, Reynolds number and Mach number are refreshed automatically. For example, when "airfoil with-camber" is selected, the 2-D animation of the stream lines is displayed in the 2-D area. Alternatively, the students can click the output buttons "Lift Force", "Coefficients" and "Distribution" in the 2-D animation area to display the corresponding outputs (see Figure 6, Figure 7 and Figure 8). In order to better visualize the wind tunnel, the students can also click the button "3D Picture" in order to render the virtual wind tunnel laboratory with an airfoil, whereby the students can even "operate" the virtual wind tunnel by pressing the "Start" and "Stop" buttons.

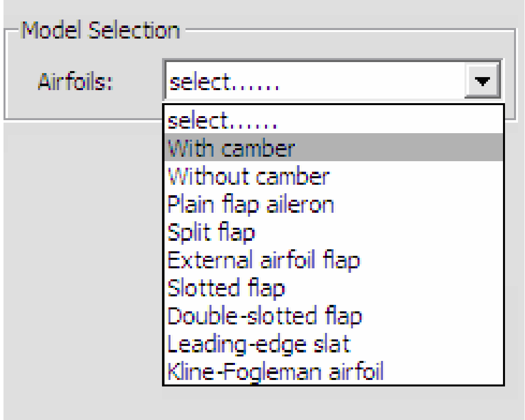


Figure 5: Airfoil model selection panel

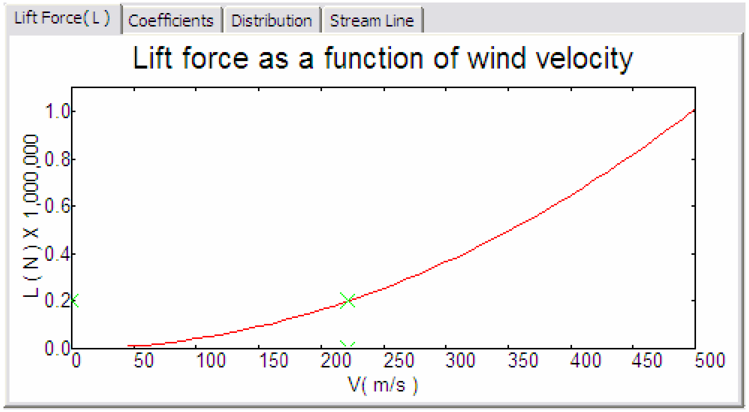


Figure 6: Lift force as a function of velocity

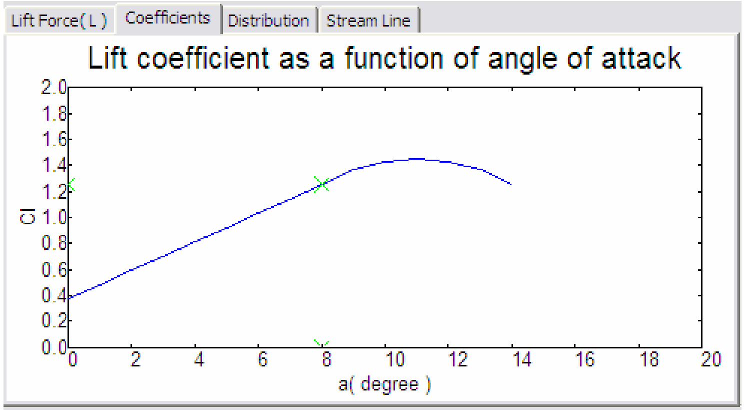


Figure 7: Lift coefficient as a function of angle of attack

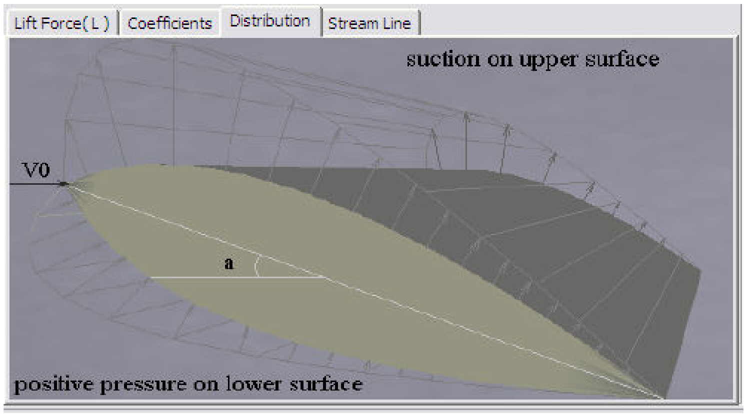


Figure 8: Lift force distribution

The virtual laboratory contains the main characteristic parameters of airfoils. Airfoils are designed to generate a lift force, *Lf*, normal to the free stream flow. Performance characteristics of airfoils are normally given in terms of the dimensionless lift coefficient and drag coefficient. For a specific angle of attack, α, the lift coefficient C_L is a constant, even for different velocities *V*. Table 1 summarizes the relationships between the parameters that determine the lift forces of the airfoils.

Table 1: Airfoil parameters

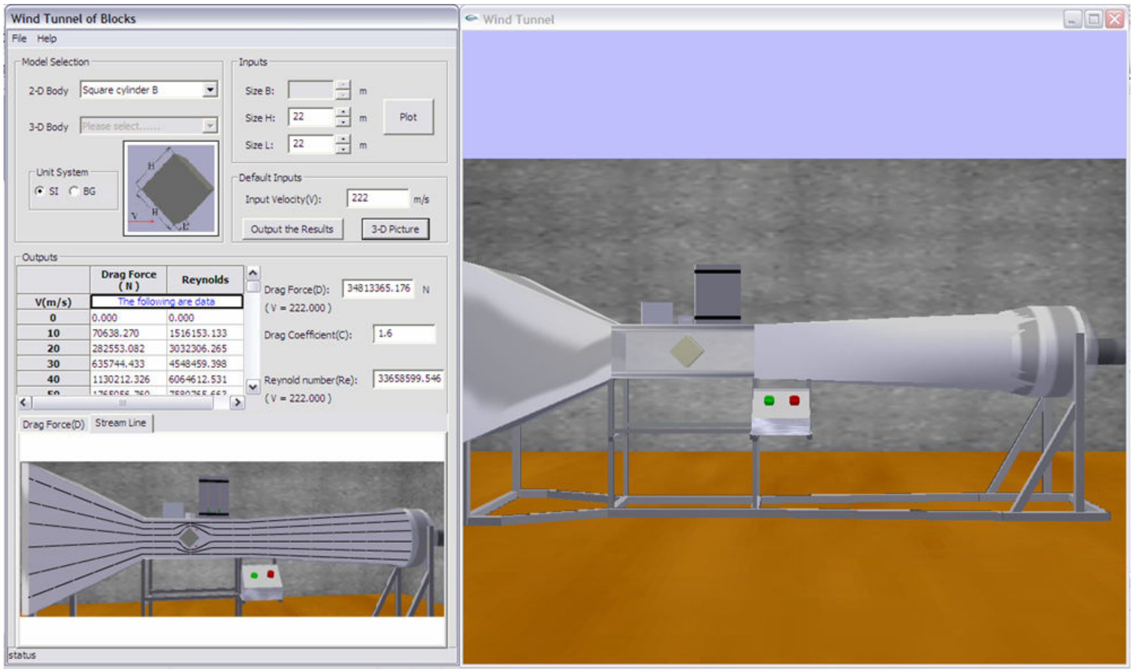
No.	Parameters	Equations	Notes
1	Lift coefficient	$C_L = Lf/(q_0 S)$	S: planform area of airfoil
2	Drag coefficient	$C_D = Df/(q_0 S)$	Df: drag force
3	Dynamic pressure	$q_0 = 0.5\rho V_0^2$	ρ: density of air
4	Lift force	$Lf = C_L q_0 S$	q_0: dynamic pressure of air
5	Reynolds Number	$Re = Vb/v$	V: free-stream velocity v: viscosity of air b: characteristic length
6	Mach Number	$Ma = V/a$	a: speed of sound V: speed of airplane

Experimental results for the lift coefficients for the airfoil types listed in Figure 5 are summarized in Table 2. In these relationships, the working area of the angle of attack α is different for different airfoils.

Table 2: Experimental lift coefficients for various airfoil types

No.	Airfoils	Equations of lift coefficients	Angle of attack
1	With camber	$CL1=0.1096\alpha$ $CL1=-0.0017\alpha^2+0.05\alpha+0.96$	$(0^o<\alpha\le 12^o)$ $(12^o<\alpha<18^o)$
2	Without camber	$CL2=0.1096\alpha+0.357$ $CL2=-0.0224\alpha^2+0.493\alpha-1.2586$	$(-3^o<\alpha\le 8^o)$ $(8^o<\alpha<18^o)$
3	Plain flap	$CL3=0.103\alpha+1.542$	$(-3^o<\alpha<10^o)$
4	External airfoil flap	$CL4=0.103\alpha+1.714$	$(-3^o<\alpha<10^o)$
5	Slotted flap	$CL5=0.103\alpha+2.114$	$(-3^o<\alpha<9^o)$
6	Double-slotted flap	$CL6=0.103\alpha+2.629$	$(-3^o<\alpha<7^o)$
7	Leading-edge slat	$CL7=0.103\alpha+0.743$	$(-3^o<\alpha<15^o)$
8	Kline Fogleman airfoil	$CL8=-0.0011\alpha^2+0.0931\alpha-0.3548$	$(4^o<\alpha<50^o)$

Body Wind Tunnel: The virtual wind tunnel can also be used to conduct experiments on various bodies such as cubes, cups and disks. Figure 9 depicts the graphical user interface of the virtual laboratory with various bodies. Firstly, the students need to select a 2-D or 3-D body in the "Model Selection" panel. Then, they can input the necessary parameters, such as the sizes of the selected body, and click the "Plot" button to generate the outputs. At most three parameters (size B: width, size H: height and size L: length) are used to describe the 2-D or 3-D bodies with various cross sections. 2-D bodies are described by at least two size parameters. For example, one can use diameter B and length L to describe a "Round Rod". The students are automatically prompted for the necessary input parameters, for instance "Size H" and "Size L" for "Square cylinder". After the body has been selected, stream lines can be displayed. The graphical user interface for the virtual 3-D wind tunnel with bodies was designed similarly to the airfoil wind tunnel.



2-D Body: Square cylinder B

3-D Body: Please select......

Unit System: ● SI ○ BG

Size B: m

Size H: 22 m

Size L: 22 m

Input Velocity(V): 222 m/s

V(m/s)	Drag Force (N)	Reynolds
	The following are data	
0	0.000	0.000
10	70638.270	1516153.133
20	282553.082	3032306.265
30	635744.433	4548459.398
40	1130212.326	6064612.531

Drag Force(D): 34813365.176 N
(V = 222.000)

Drag Coefficient(C): 1.6

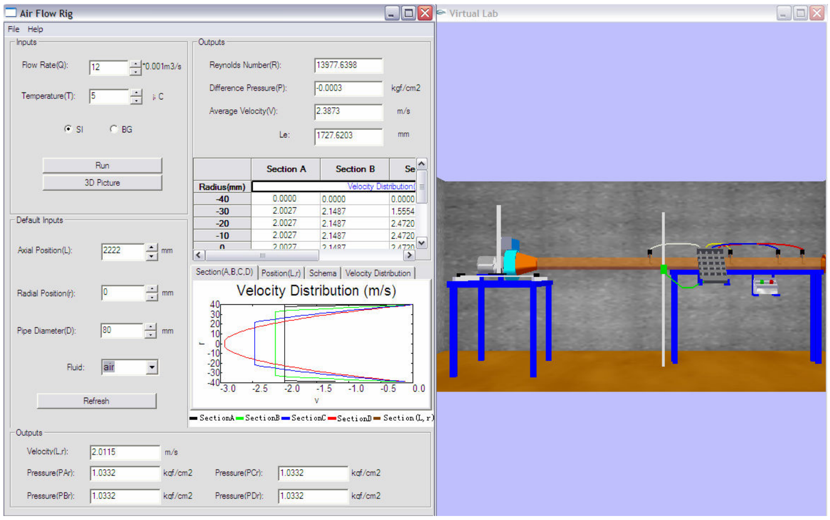
Reynold number(Re): 33658599.546
(V = 222.000)

Figure 9: Graphical user interface of virtual wind tunnel laboratory with bodies

Virtual Air/Oil Flow Rig Laboratory

While an experimental air flow rig is usually an open system, a hydraulic system must be a closed system with the liquid circulating. Therefore, we designed different virtual laboratories for air and oil systems.

Air flow rig: This virtual laboratory describes the internal flow of air in a pipe. An internal flow is constrained by the bounding walls. The viscous effects grow and meet to permeate the entire flow. There is an entrance region with a nearly inviscid upstream, followed by retardation of the axial flow at the walls, thus accelerating the center core flow so as to maintain the incompressible continuity requirement. At a finite distance from the entrance, the boundary layers merge and the inviscid core disappears. The tube flow is then entirely viscous, and the axial velocity adjusts slightly further. At the entrance length of $x=Le$ it no longer changes with x and is said to be fully developed. This process can be analyzed through the virtual laboratory of the air flow rig. The corresponding graphical user interface is shown in Figure 10. The main input parameters are the flow rate Q and the temperature T. Furthermore, either the SI or BG systems must be selected. In addition, the students can input specific points of interest for which the results are desired. Figure 11 and Figure 12 depict the velocity distributions at the specified points of interest in 2-D and 3-D, respectively.



Inputs

Flow Rate(Q): 12 *0.001m3/s

Temperature(T): 5 ¡ C

● SI ○ BG

Outputs

Reynolds Number(R): 13977.6398

Difference Pressure(P): -0.0003 kgf/cm2

Average Velocity(V): 2.3873 m/s

Le: 1727.6203 mm

	Section A	Section B	Se
Radius(mm)	Velocity Distribution(		
-40	0.0000	0.0000	0.0000
-30	2.0027	2.1487	1.5554
-20	2.0027	2.1487	2.4720
-10	2.0027	2.1487	2.4720
0	2.0027	2.1487	2.4720

Default Inputs

Axial Position(L): 2222 mm

Radial Position(r): 0 mm

Pipe Diameter(D): 80 mm

Fluid: air

Outputs

Velocity(L,r): 2.0115 m/s

Pressure(PAr): 1.0332 kgf/cm2

Pressure(PCr): 1.0332 kgf/cm2

Pressure(PBr): 1.0332 kgf/cm2

Pressure(PDr): 1.0332 kgf/cm2

Figure 10: Graphical user interface of virtual air flow rig laboratory

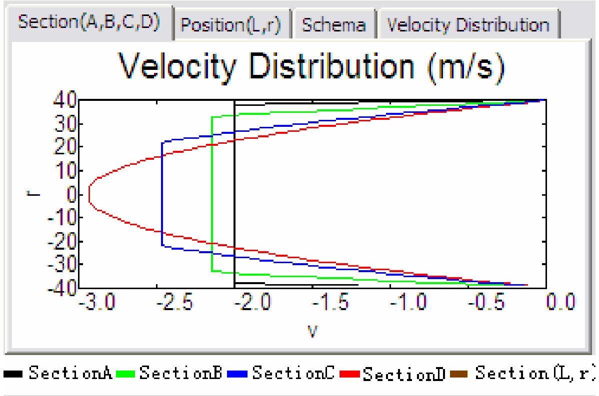


Figure 11: 2-D velocity distribution in sections A, B, C and D

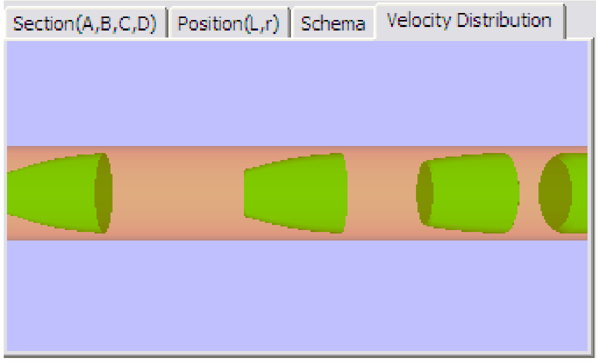


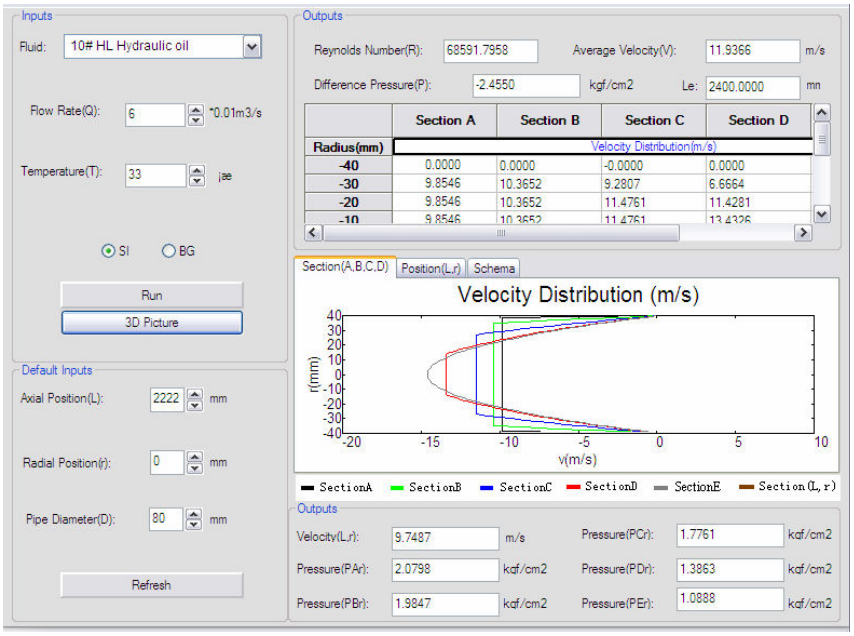
Figure 12: 3-D velocity distribution along the pipe

Table 3 summarizes the relevant fluid mechanics parameters for an air flow rig. These equations are embedded in the virtual laboratory of the air flow rig. There are several kinds of output, including a 3-D model, 2-D plotting and data tables. The students can obtain the results for the Reynolds number *Re*, the average velocity *V*, the pressure difference *ΔP* and the entrance length *Le*.

Table 3: Relevant fluid mechanics parameters for air flow rig

No.	Parameters	Equations	Notes
1	Average Velocity	$V = Q/A$	A: section area of pipe Q: flow rate
2	Reynolds Number	$\mathrm{Re}_{air} = (p/RT) \times \mu_0 (T/T_0) \times 10^7$	R: universal gas constant T: temperature in kelvins
3	Pressure Difference	$\Delta P = 0.5hm\rho V^2 + 0.5hl(L/D)\rho V^2$	hm = 0.02: head loss hl: treated as smooth pipe
4	Entrance length	$\mathrm{Le} = 0.06\,\mathrm{Re}_{\mathrm{air}}\,\mathrm{d}$	d: pipe diameter

<u>Liquid flow rig</u>: Many hydraulic systems use water as transfer medium while airplane oils, hydraulic oils and lubrication oils are common industrial oils. The liquid flow rig incorporates the properties of these liquids similarly to the air flow rig. Figure 13 depicts the graphical user interface of virtual liquid flow rig laboratory. Figure 14 shows a 3-D rendering of the liquid flow rig. The students first select the liquid to be used in the input panel, such as for instance "10# hydraulic oil". Then, the students can input the necessary input parameters including the flow rate (e.g. 0.06 m³/s) and the temperature (e.g. 33°C), and press the "Run" button. The outputs displayed in the graphical user interface are shown in Figure 13. If so desired, the students can obtain the output for a specific point, such as for instance at axial L = 2222 mm, radial r = 0 mm and pipe diameter d = 80 mm. Furthermore, the Reynolds number, pressure difference and entrance length are displayed when the "Refresh" button is pressed. Similarly to the virtual wind tunnel, in the virtual liquid flow rig the users can generate an animation of the liquid flow using the "Start" and "Stop" buttons.



Inputs

Fluid: 10# HL Hydraulic oil

Flow Rate(Q): 6 *0.01m3/s

Temperature(T): 33 jæ

● SI ○ BG

Default Inputs

Axial Position(L): 2222 mm

Radial Position(r): 0 mm

Pipe Diameter(D): 80 mm

Outputs

Reynolds Number(R): 68591.7958

Average Velocity(V): 11.9366 m/s

Difference Pressure(P): -2.4550 kgf/cm2

Le: 2400.0000 mn

	Section A	Section B	Section C	Section D
Radius(mm)	Velocity Distribution(m/s)			
-40	0.0000	0.0000	-0.0000	0.0000
-30	9.8546	10.3652	9.2807	6.6664
-20	9.8546	10.3652	11.4761	11.4281
-10	9.8546	10.3652	11.4761	13.4326

Outputs

Velocity(L,r): 9.7487 m/s

Pressure(PAr): 2.0798 kgf/cm2

Pressure(PBr): 1.9847 kgf/cm2

Pressure(PCr): 1.7761 kgf/cm2

Pressure(PDr): 1.3863 kgf/cm2

Pressure(PEr): 1.0888 kgf/cm2

Figure 13: Graphical user interface of virtual liquid flow rig laboratory

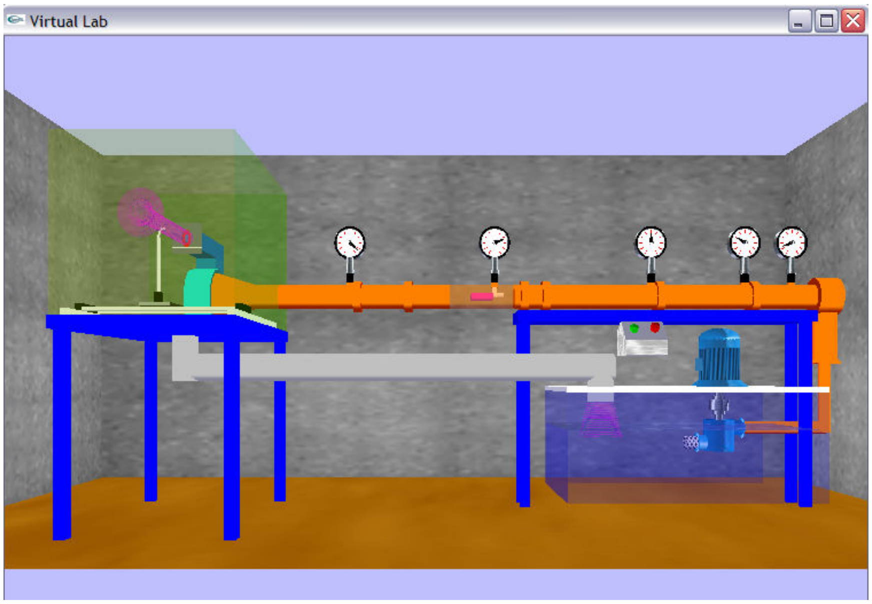


Figure 14: Virtual equipment of flow rig

Conclusions

Virtual student laboratories are emerging rapidly. They are expected to play an increasingly important role in engineering and science education. This article describes an interactive tool for teaching undergraduate fluid mechanics. Six virtual laboratories were designed and implemented at SIT, including an airfoil wind tunnel, a body wind tunnel, an air flow rig and a liquid flow rig. The Python programming language was found to be a powerful tool for the implementation of virtual laboratories.

Student can control the shape, size, and inclination of the airfoil and see a schematic drawing of the airfoil with varying conditions to explore the effects of flow. The effects of airfoil camber, thickness and angle of attack can be studied interactively. This tool also allows student to measure lift force acting on an airfoil set at various angles of attack.

Expansion of the set of available virtual fluid mechanics experiments include an air flow jet, a liquid flow jet, a Reynolds number rig, a Bernoulli equation rig, a stream line rig and a loss coefficients of hydraulic elements rig.

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