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Experience in Teaching Turbomachinery Using Advanced Dedicated Software

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ABSTRACT

Whereas turbomachinery design has evolved over the last two decades, updating instruction on the topic to reflect the new prevailing methods and techniques remains a challenge. Part of this challenge stems from the diversity of technologies covered in the courses; part of it ensues from the extensive use of software by industry designers. A review of the literature shows that varying degrees of complexity in software have been adopted for teaching, and that numerical experimentation has in some universities replaced laboratory experimentation. This paper describes the experience and outcomes of teaching turbomachinery to senior engineering students using advanced design software. The cases and results analyzed by the students for axial compressors and turbines are discussed, and the results of the effort are evaluated from the somewhat different perspectives of the students and of the instructor. Whereas the use of the program must be viewed in the context of the entire course (two hardware labs are held along with conventional lectures and homework), the use of design software could be seen to multiply the skills of the students, enabling broad 3-D design considerations and visualization seldom possible otherwise. In addition, an understanding of prevailing stresses is initiated with the software.

INTRODUCTION

In the age of Information Technology (IT) , it becomes necessary for engineering professors to seek innovative ways to deliver instructional material that relies on IT, while preserving instruction based on timeless physical principles. In the traditional engineering classroom setting, students receive information that they then apply to homework problems or projects, the latter usually involving some aspect of active learning. In other courses planned with a strong active learning component, the students directly participate in the planning, design and/or construction of short-term projects. Whereas this hands-on approach is quite effective towards generating student interest and increasing engineering skills, it can generally be applied to only small scale turbomachines, because larger machines require much more knowledge and their complete design is much harder to supervise. The wider scope of turbomachines calls for general, comprehensive learning tools whereby students can apprehend principles and concepts, and generalize what is learned as a base for innovation or for insightfully practicing the profession.

Our experience and goals are neither unique nor isolated. Integration of software tools into the undergraduate curriculum is a recurrent topic in the literature. In particular, software for design of a high-pressure turbine cooling system was incorporated by Mund et. al. (2002). This approach was aimed at maintaining the international level of the education offered by the host institution, further enhancing the understanding of the design process, team work and time management. Feedback from the students was obtained during project unfolding. The experience was well received by the students, but it demanded considerable effort from the faculty involved, especially regarding the application of engineering judgment during the design process. The international reach of the project was apparently strained due to cultural differences, illustrating the difficulties of offering an information-intensive course across international boundaries. In 2007, Turner at al. used a validated design system (T-AXI) for educators and students, of sufficient depth to be of interest to actual designers. This software suit incorporates a blade geometry generator. The approach to loss estimation, as well as results obtained with T-AXI (which is available for download) were documented. Cravero and Marini (2007) packaged their design tools and experience in software to support radial inflow turbine design. Their projection was that the package could be used for design and/or analysis, and that it enhanced the student's experience towards working in industry. Map generation is the specialty of this software, a most valuable component for teaching. No evidence of learning experiences was offered by the authors of the two previously cited publications.

A different tack was adopted by Marineu and Reggio (2007), in that their contribution was aimed exclusively at allowing students to acquire intuitive knowledge via a graphical interface somewhat reminiscent of those found in power plants to monitor component performance. A toolbox was developed within the Matlab environment to serve as the window between the user and the program. The toolbox employed a visual interface in which the user entered design variables and observed the response. The paper documented the approach to loss calculation, but the user did not need to know the intricacies of the calculations to gain a working knowledge of the preferred design parameters. Whereas intuitive knowledge is clearly important, other aspects of turbomachines are worth exploring. The paper documented the analysis with correctness devoid of detail, but references to the methods employed were cited. The topic of axial compressor design using T-AXI, and its possibilities when linked to CompEdu (2004), were recorded by Bruna et. al. (2007). The paper contained detailed results derived from compressor analysis. Considerable effort was required from the users previous to interaction with the program, in that reading references to previous work on the compressor under consideration was recommended. From the results, it was possible to conclude that T-AXI is indeed a flexible and comprehensive tool, yielding results compatible with practice.

A recent study (Wiggins, 2008), focused on using MathCad® to design complete thermal systems, including the stage-to-stage design of a subsonic steam turbine. This work was oriented towards documenting the technical results and the student experience. Notably, the professor required the students to write software that he could easily verify with his own, prewritten material. To this end, the flexibility of the chosen platform was instrumental. In general, the students response to a survey indicated that they successfully learned about the steam path in a turbine. The most recent work of Gutzwiller, Turner and Downing (2009), identified the lack of transparent design and visualization tools as a crucial problem in turbo machinery courses. We agree with their assessment of a vexing, long-standing problem: attempting to teach in the 2-D of the blackboard what is essentially a 4-D problem (3 geometrical coordinates and time). In this contribution, the virtues of the software were summarized from the perspective of blade-disk designers.

An example combining theory, experimentation and industrial practice is the seminal approach of Sjolander and Saravanamuttoo, 1989. In their innovative delivery, knowledge was integrated by covering the whole spectrum from thermodynamics and thermo fluids to solid mechanics. In addition, close ties with local industry were fostered. It is clear from this effort that the feedback in terms of research questions and hiring, that only industry can provide, is irreplaceable as a motivational tool for students.

Summarizing, from courses offered almost 20 year ago to the most recent approaches, only the laws of Thermodynamics and the principles of turbomachines have stayed invariant. Individual universities and learning centers have adopted different mixes of empiricism and design/analysis, and among those developing/adopting software (and reporting their experience) some recorded relatively simplified tools, whereas others reported rather sophisticated ones. However, a neatly defined picture emerged: as incursions in experimentation became less widespread due to cost and to the lack of generality of the experience, the need to implement models that were general, flexible and numerically robust became apparent. Specifically, the abilities to generate and analyze creative designs from both a thermofluids and a material strength standpoint became more urgent. Whereas nothing can really replace experimentation with components and, ultimately, the building of a turbomachine, dealing with relevant software has prepared students, and in many cases, reduced the number of empirical iterations.

In this paper, we describe our experience in teaching a one semester course on gas turbines using AxSTREAM®. Rather than focusing on the overall capabilities of the software, we concentrate on the description of a few aspects of it, namely the ones that were employed to enhance teaching. Creativity in engineering design must be based on a firm grasp of the physical principles that codify our shared understanding of reality. Therefore, instruction is aimed at describing the application of those principles, jointly with illustrating how the software builds upon them to relieve the designer of tedious calculations. Careful interpretation of results is a must in this endeavor.

APPROACH

Learning about turbines and software jointly is an activity that we deem to be best accomplished progressively. Our teaching experience indicates that students need to understand ideal flow around blades and vanes, and the loss mechanisms that lead to a reliable estimate of isentropic efficiency. Losses, and their attending explanations in terms of flow behavior, can only be appraised if a reliable 3-D view of a stage is present in the mind of the student. Hence, the ultimate objective is the 3-D visualization of a stage, although intermediate levels must be successfully completed before the software grants access to 3-D tools. Our one semester experience can be divided into four phases.

Phase I. A series of brief assignments on turbines: Since the first half of the semester is aimed at the thermodynamics of Brayton cycles and cogeneration, we adopt the tack of issuing relatively simple assignments while the theory of cycles (ranging from power generation to turbofans) is worked upon. We seek to qualify the students (41 in the Fall semester) to:

1. become proficient at interpreting the thermodynamics of a stage,
2. understand how the blade profile in a 2-D design influences the stage Mach numbers and losses
3. glimpse and partially apply the 3-D design capabilities of the software.

Levels 1, 2 and 3 are depicted graphically in Fig 1. The assignments are geared to help students access the levels and interpret the output. Because of the limited information available to the students on thermofluids at the time of the assignments, every effort is made to guide them gradually and to help them develop an intuitive understanding of what the program calculates for them. All the while, they are encouraged to explore and innovate, for numerical experimentation with judicious feedback is a learning avenue that we find effective in the long term.

Given turbine inlet conditions, rotational speed, mass flow rate and discharge pressure, the software determines the number of stages, cross sections, metal and flow angles, losses and fluid properties before and after each stage. This determination optimizes efficiencies by searching for the optimal mean line flow path. The results are conveniently presented as shown, for instance, in Fig 2. The h-s diagram has been magnified to focus on one stage. State point variables can be displayed by pointing to them with the mouse. A number of variables can be graphed on the upper right plot space for each stage. Thus, flow and metal angles, degree of reaction and losses can be readily appraised. The sketch in the lower right illustrates the stator (blue) and rotor (red) for each stage. The cross sections are determined by the program, but those (and other variables as well) can be edited graphically by the student.

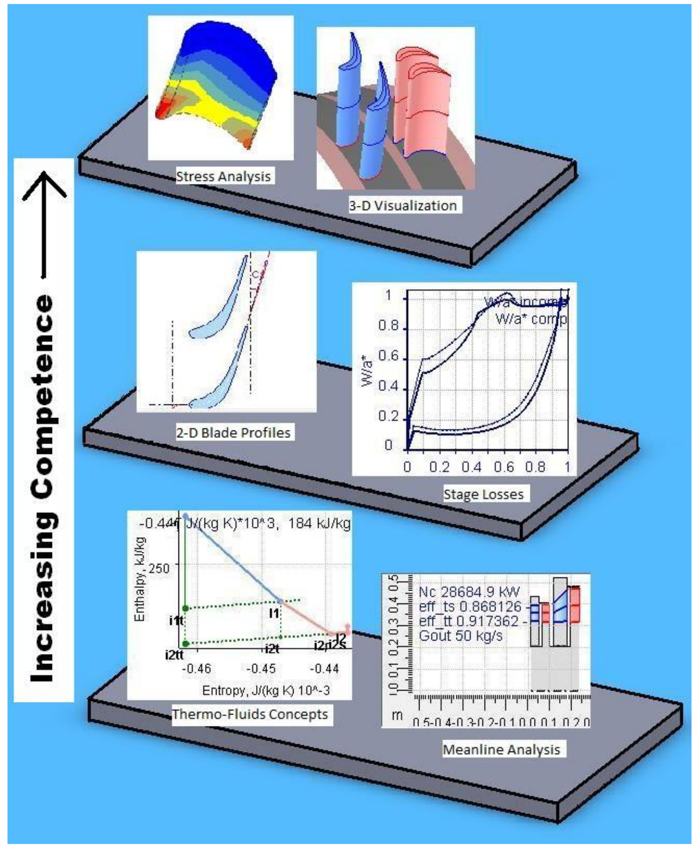

Fig 1. The three competence levels for the semester.

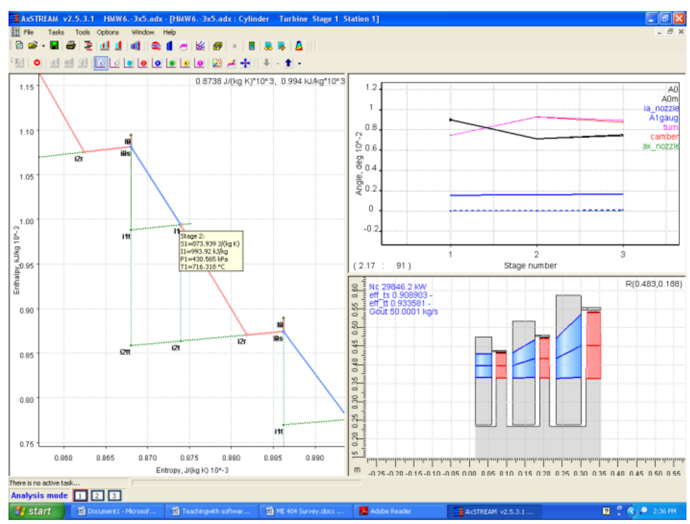

Fig 2. Output showing design based on meanline path optimization.

For instance, students were asked to vary the cross sections to see the effect on efficiency. Armed with only elementary knowledge of stage configurations, the class undertook the assignment, and freely changed and matched the cross sections. Abridged results are shown in Table 1. It is remarkable that by manual experimentation with the cross sections the students were able to favorably affect the efficiency. The process is instructive, for as the cross sections are changed, stage velocities, efficiencies and capacities are instantly updated, allowing conceptual appraisal of interrelations among stage variables. Whereas converging cross sections in gas turbines are rare, at this level of preliminary design they would seem to merit some consideration.

Table 1: Stage cross sections results (10 students).

	Constant	Converging	Diverging
Stator Cross Section	3	4	3
Rotor Cross Section	2	5	3
	Before editing cross sections		After editing cross sections
Average Efficiency	0.78		0.81

The software allows flow path refinements, and the user can select from a multiplicity of feedback information. After completing a flow path design (Level 1 in Fig 1) the students are asked to load the custom blade profile supplied by AxSTREAM for each stage. Then they are asked to concentrate on the compressible plot of Mach number (W/a*) vs. normalized distance from the leading edge as a design tool, Fig 3, right pane. This figure also shows one tool with sliders (lower left), whereby the user can adjust blade parameters. While the blade/vane angles and chord are kept constant by the program, the student can edit the profile via various tools, notably the stagger angle and blade thicknesses.

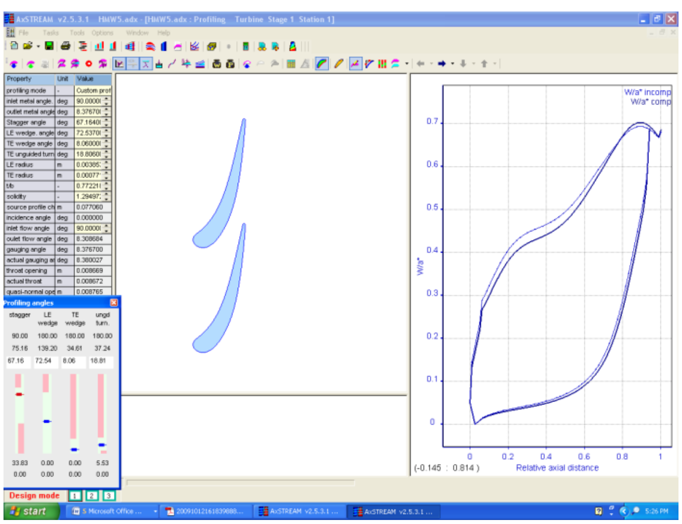

Fig 3. Adjusting the vane profile

As the profile is edited, the Mach numbers in the suction and pressure sides of the blades change. The stated objectives are to maximize the area enclosed by the diagram, to keep the Mach numbers below or not too far above one, and to obtain curves that are reasonably smooth and exhibit convergence at the trailing edge. As the students seek the Mach diagram for each stage, variations in stagger and other angles and loss coefficients are noted. Table 2 contains some results, showing the most variability in stagger, LE wedge and TE wedge angles, for four students with substantially correct Mach number plots. Losses and solidity are approximately the same for all of them. An inspection of Fig 1 shows that at this point in learning the program, students are accessing the second level indicated in the figure.

Table 2. Selected results of profiling study for a rotor

	Units	Student 1	Student 2	Student 3	Student 4
Inlet metal angle	deg	90	90.00	90.00	90.00
Outlet metal angle	deg	8.37	7.528	8.377	7.52
Stagger Angle	deg	71.19	69.69	62.46	71.05
LE Wedge Angle	deg	102.0	50.00	61.791	67.1
TE Wedge Angle	deg	6.716	1.136	13.43	8.3
TE Unguided Turning Angle	deg	6.716	7.00	28.209	10.8
LE Radius	m	0.003	0.003	0.0039	0.003
TE Radius	m	0.0007	0.0007	0.00077	0.0007
t/b	-	0.751	0.7722	0.7722	0.751
Solidity	-	1.329	1.33	1.295	1.329
Loss Coefficient	-	0.0393	0.0446	0.0402	0.0454

Although design is the product of multiple (ordered and judicious) compromises, singling out one variable was deemed developmental for our students. Hence, in another assignment they were requested to optimize the loss coefficient in the "profiler", using the editing tools available to them. The results were substantially reduced loss coefficients, although the Mach numbers did exceed one in a number of cases. The results are summarized in Table 3.

The users did reduce the losses below the values of Table 2, and the third stage rotor loss coefficient exhibited repeatedly the minimum loss. Again, this exercise developed competence at Level 2. The last assignment to complete the instruction consisted of familiarizing the students with some aspects of level 3. The assignment consisted of simply visualizing and printing a stage (Fig 4) after completing designs at levels 1 and 2. Two weeks before the assignment, the students participated in two labs, one running an actual turbine (SR-30 thrust demonstrator), and another inspecting a small helicopter turbine, so as to reinforce the visual knowledge gained at this level. The vanes and blades of Fig 4 are devoid of any 3-D features. Still the visualization tool, together with the labs, fostered clear understanding of the configuration and function of a turbine stage.

Table 3. Manual search for the lowest loss

Student	Highest Loss Coefficient		Lowest Loss Coefficient	
1	0.0326	Stage 1 Stator	0.018	Stage 3 Rotor
2	0.019	Stage 3 Stator	0.013	Stage 2 Stator
3	0.0394	Stage 2 Stator	0.0249	Stage 1 Rotor
4	0.0297	Stage 3 Stator	0.0122	Stage 3 Rotor
5	0.028	Stage 3 Stator	0.0171	Stage 3 Rotor
6	0.036	Stage 3 Stator	0.0196	Stage 3 Rotor
7	0.023	Stage 1 Rotor	0.0179	Stage 3 Rotor
8	0.0163	Stage 1 Rotor	0.0117	Stage 2 Stator
9	0.033	Stage 3 Stator	0.0201	Stage 3 Rotor
10	0.0206	Stage 3 Rotor	0.0297	Stage 1 Stator
Most Frequent Location of Highest Loss Coefficient			Stage 3 Stator	
Most Frequent Location of Lowest Loss Coefficient			Stage 3 Rotor	

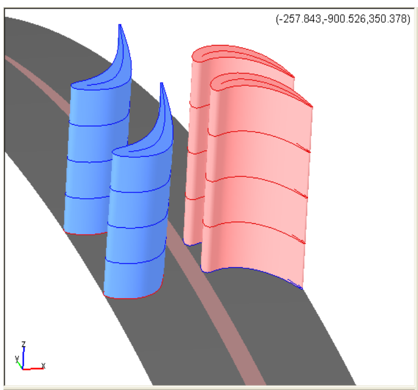

Fig 4. 3D view of unedited stage.

Phase II. 3 D features: This phase objective is to familiarize the students with some aspects of 3D design. In a first assignment, 3D features are introduced by varying the camber of the vanes and blades along the span. To do this, the software must be placed in the "Analysis mode". Then the student can vary the inlet and exit metal angles for each stage component, and also the stagger angle. A 1D/2D analysis must be carried out after refining the design. Alternatively, the designer can obtain the solution of the Euler equations for the 3-D shape, but this was not required from the class due to time constraints. A typical stress calculation obtained during this phase is shown in Fig 5.

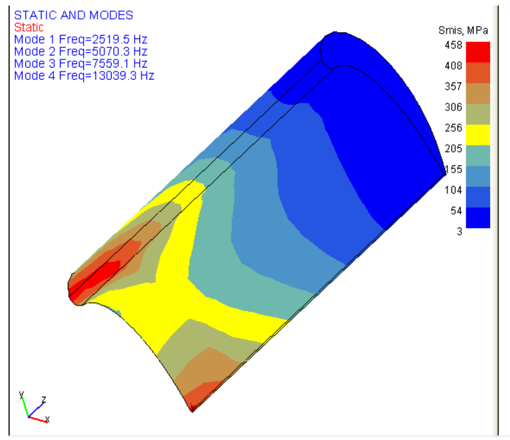

Fig 5. Output of stress analysis

The peak stresses occur at the LE and TE, close to the hub. Decreasing those stresses would require more material in the hub, a fact that was brought to the student's attention when necessary. Likewise, avoiding excitation of any of the 4 vibration modes is important for a sound design.

A second assignment in this phase involves generating the vane and blade angles to create a free vortex design. The students then enter the calculated angles to obtain a 3-D view of blade and vanes with the desired free vortex azimuthal velocities. This exercise is once again followed by blade/vane stress and modal calculations.

Phase III. A turbine project: A two-week project requested from the students was to extract the maximum possible amount of power from an air stream, given the following conditions:

Inlet temperature: 1170 K
Inlet pressure: 700 kPa
Exhaust pressure: atmospheric (100 kPa)
Mass flow rate: 80 kg/s

Expectations for the design covered all three levels of Fig 1, and were met appropriately by most. The teams had to select the number of stages and the rotational speed of the turbine, and produce blade profiles that would pass the AxSTREAM curvature analysis. Of particular interest is the range of turbine capacities achieved by the various teams (There were 13 entries in total, but two were disqualified because of errors in the input or in the profiling.) The final results are summarized in Table 4 below.

Table 4. Summary of project results (11 teams)

Mean Capacity	37.14 MW
Standard deviation	0.84 MW
Minimum	35 MW
Maximum	38.2 MW

Whereas the dispersion for capacities is small, it is clear that at least on paper, not all designs are equal, and that careful attention to detail can result in a few extra kW of turbine capacity.

Phase IV Axial compressor design: Traditionally, axial compressor stage configuration and losses are hard to impress upon the students, not to mention of 3-D design aspects. The nature of diffusion in both blades and vanes, and transonic issues arising in tip regions are complex problems that designers must address with varying degrees of sophistication. Because the software offers effective tools to ascertain the prospects of a design, the intricacies of producing a credible geometry are greatly reduced. For our instructional purposes, compressors require the same three levels of competence as turbines. But the learning process can be compressed because the students are by now familiar with the program interface and its tools.

In the first compressor assignment, students were asked to produce a thermal design capable of a pressure ratio of 1.6, with a mass flow rate of 7.8 kg/s at 15,000 rpm and inlet stagnation pressures and temperatures of 100 kPa and 288 K. The assignment contained the requirement to verify the initial design with the 1D/2D streamline solver, after creating custom profiles for the stator and rotor of each stage. Streamline curvature methods (Lakshminarayana, 1996) have the appeal of being recognized universally in industry, and of requiring short computational times. An iterative procedure yields the stream lines that satisfy the continuity equation globally and the radial momentum equations. Compliance with the Buri criteria to avoid boundary layer separation is also requested. The outcome of this exercise on compressors is outlined in Table 5. The results are classified as acceptable (i.e. meeting the target pressure ratio with no errors) or marginal (i.e. yielding pressure ratios below the target with no errors). In addition to pressure ratio, the angular flow departure from the blade angle (Delta) in degrees, as well as the average loss factor are given.

Table 5. Selected Axial Compressor Variables

	Acceptable		
Student	**Pressure Ratio**	**Delta (degrees)**	**Loss Factor**
1	1.59	5.55	0.035
2	1.64	6.78	0.029
3	1.60	5.33	0.037
4	1.59	5.32	0.037
5	1.64	5.31	0.037
	Marginal		
6	1.38	0.0	0.10
7	1.14	6.61	0.17
8	1.44	7.46	0.15
9	1.14	4.23	0.26
10	1.37	4.65	0.25

Another assignment dealing with compressors endeavored to establish familiarity with 3-D stage visualization. Except for a few students (approximately 10%), a suitable perception of 3-D compressor stage configuration was realized by the class.

FEEDBACK

Student feedback was requested twice during the semester via anonymous surveys. The first survey was dedicated to ascertain the intuitive understanding of the functional aspects of a turbine stage. At this point, students had gained proficiency to Phase I, and basic concepts of compressible flow and compression shocks had been introduced. However, turbine stages had only been introduced in qualitative form. To ascertain the effectiveness of using the design tool somewhat intuitively, the questions noted in Table 6, First Survey, were asked. In interpreting the results, it must be borne in mind that lab experiments with a small turbojet and inspection of a small helicopter turbine had been conducted in small groups. Clearly, the students gained good knowledge of how losses degrade performance, how entropy is useful in gauging the losses, and how rotational speed influences turbine design. Also, the quality visualization tools of the software and the labs enabled a lucid perception of 3-D geometries.

Table 6. Survey results.

First Survey	
	Average Score (out of 5)
I have intuitively learned the geometry of a gas turbine stage	3.91
I have learned how changing the cross section of a channel affects efficiencies	3.82
I have a feeling for the degree of reaction as a measure of expansion in a stator	2.94
I have a feeling for how the rotational speed influences the characteristics of the turbine	3.73
I have seen how losses and entropy increases correspond to each other	3.76
I can visualize the 2-D geometry of blades/vanes	4.45
I can visualize the 3-D geometry of a blade and stage in a turbine	4.27
Second Survey	
I can perform analysis and design of axial compressors and turbines to the 1D/2D level	4.22
I can enter angles to change the 3D configuration of a turbine blade	4.33
I understand the variables that go into designing compressor/turbine stages by hand	3.48
I understand how a turbofan works	3.67

The second survey was requested at the end of the course, when both basic principles and software had been introduced and tested. The results of the second survey are summarized also in Table 6, Second Survey. The second survey shows that the students feel confident when applying AxSTREAM. The basic understanding of stages and turbofan cycles seems to be less than perfect, yet of reasonable quality.

CONCLUSIONS

Coupling of theoretical and IT design knowledge augments the capability of students to contribute to the industrial endeavor. Theoretical introduction to a topic seldom illustrates the level of detail required by final designs. For instance, the computation of stage angles does not require specification of a blade profile. A mean line blade profile may not be suited for the hub or for the tip of a blade. Similarly, an aerodynamically correct blade profile may be unsuited because of stress levels or excitation frequencies. By introducing the multiple dimensions of design required by turbomachinery early in the instruction process using AxSTREAM, the students were able to develop insights that traditional instruction is unable to attain in the same time frame.

Teaching with software is challenging, because the lack of user experience on turbo machinery integrated design (i.e. factoring all aspects of marketing and manufacturing) conspires against meaningful interpretation of results (Mund et. al.,2002). Yet, the 1D-2D approach chosen by the developers of AxSTREAM was found instrumental for developing simultaneously thermofluids basic knowledge and user competence. The students were able to calculate stage angles and produce profiles that contained losses. They also became proficient at incorporating 3-D notions into their designs. This level of competence is unusual for a first course in Turbomachinery, and could not have been realized without the software and its technical support. A deeper understanding of the attending thermofluid principles would have been desirable, but the information was made available via lectures and notes, and the students could indeed recover it should the need arise.

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