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Using Familiar Analogies to Teach Fundamental Concepts in Thermo-Fluids Courses

Abstract

By the time engineering students enroll into Thermodynamics, Fluid Mechanics, and Heat Transfer courses, they are relatively savvy with math and basic science concepts. Therefore, the calculations required in the Thermo-Fluids courses are not especially difficult. Conversely, many of the fundamental concepts and physical understanding of energy, fluid mechanics, and heat flow are difficult to grasp. The students have observed solid mechanical kinematics and dynamics first-hand all of their lives, but energy, fluid flow, and heat flow are sometimes not readily visualized.

With this in mind, a useful method to explain the concepts is via everyday/familiar/folksy analogies. This paper contains a sampling of some analogies that can be used to teach thermal fluid concepts as varied as entropy, the no-slip condition, velocity profiles & boundary layers, numerical marching solutions for heat flow, and more. The authors also offer advice for creating and using your own analogies, and intend to encourage the reader to add to the growing list of teaching analogies.

1. Introduction

> "As dry leaves before the wild hurricane fly,
> When they meet with an obstacle, mount to the sky;
> So up to the house-top the coursers they flew,
> With the sleigh full of toys — and St. Nicholas too."
>
> \- "A Visit from St. Nicholas," Clement Clarke Moore

All the way back in 1823, Moore found that a fluid flow analogy was the best way to describe the flight of Santa's sleigh. And he was not even an engineering professor! With an interesting twist, engineering professors can use Moore's analogy in the classroom. Here we have the dry leaves as "markers" in a stagnation flow and, as they rush toward the wall, must turn the corner and move upward.

Much research literature establishes that most students are visual learners; material is better comprehended and retained when a student can see or visualize the concepts being taught.[1, 2] While energy, fluid flow, and heat flow can be experienced and felt, they generally cannot be seen. For this reason, thermal-fluids instructors should consider using everyday analogies – familiar or folksy comparisons – to describe difficult-to-comprehend concepts. In fact the influential publication called "The Seven Principles for Good Practice in Undergraduate Education" stressed that students must relate what they are learning to past experiences.[3] Keep in mind that analogies are different than classroom examples. For instance, if a student does not grasp the concept of no-slip at a surface and the boundary layer, no amount of boundary layer examples is going to convey the physical concept of a boundary layer. With that in mind, use analogies early in the introduction of a thermal-fluid concept; the examples can then follow.

Also, the practice of active engagement has been well proven to be an effective means of student learning.[4] Many of the analogies presented in this paper are "active" analogies in which students become directly involved in demonstrating the analogy. Many involve responses from the students, and one involves students moving about and acting out the analogy. While this paper cannot be comprehensive to cover all of the major thermal-fluids concepts with analogies, it is intended to give the reader a start and encourage the development of more. Surprisingly, although the use of analogies is often quite helpful, with the exception of a few textbooks mentioned herein, the authors were unable to find much written about their use.

2. Fluid Mechanics

We begin with fluid mechanics quite simply because this subject is easiest for everyday analogies, and produces some of the most interesting.

Student struggle with the reality that a fluid is attached at a solid surface, regularly referred to as the no-slip condition. In a laminar flow, layers (laminar from the Latin word laminae – literally meaning layers) must slide one over the other. A layer of velocity gradient is then created near the surface from zero velocity to the freestream velocity called a boundary layer. A useful analogy is as follows: Take a deck of playing cards which will act as the fluid. Place the deck on the table top with your hand firmly on top of the deck. Your hand is the freestream velocity (or centerline velocity for a pipe flow). Pull your hand horizontal to the surface. The top card will stick to your hand, the bottom card sticks to the table and you fan/spread the cards out Vegas-style. Each card is like a layer of molecules, each feeling the sliding effect but to a lesser degree from one atop it. If you don't fan the cards out completely, you can also illustrate the concept of an entrance length (entry region) in a pipe. Beware, you need to practice this if you actually demonstrate it in class. This analogy works well simply in description without a physical card deck, or you can find a video on-line. Check for "table spread technique for card fanning" or "ribbon spread."[5, 6]

When introducing entrance loss, separated flow, reattachment points, or a wake behind a blunt body, the instructor must explain that a fluid cannot always follow the contours of a surface. Flow does not like corners, especially sharp corners. Have the student imagine a car rolling down the Interstate at 70 mph. Suddenly there is a sharp-edged eight foot drop-off. (Keep it rather dramatic.) Would the car follow directly over and straight down the edge of the cliff? Of course, the car will ramp off the cliff in an arc. Flow will behave the same way creating an unattached flow or a wake. At some point the car will come down and attach back to the road; in a similar manner the fluid will reattach at a point (with much less disastrous consequences).

When introducing flow stability and transition to turbulence, it is common for the students to assume that an unstable flow will begin transition to turbulence. Stability analysis does not predict the onset of transition to turbulence; it merely suggests that possibility of transition. The analogy here is a tornado watch versus a tornado warning. Ask the students to define a tornado watch. Usually at least one student will know that it indicates that conditions are favorable for a tornado, but there is no guarantee that one will form. Ask for a definition of a tornado warning and again someone will likely explain that it indicates that a tornado has been spotted. Likewise, instability indicates that conditions are favorable for turbulence, and transition indicates that turbulence has begun.

The concept of flow work (and rate of flow work) when analyzing a control volume is often fairly abstract to the student, especially considering that the control volume boundary is often an imaginary boundary placed within a larger fluid flow. In particular, rate of flow work is

$$\dot{W}_{flow} = \oint_{A_{cv}} p(\overrightarrow{V_r} \cdot \hat{n})dA.$$

How is a fluid doing work simply moving in and out of an imaginary control volume? This analog is a physically demonstrated one. Have one student go into the hallway outside the classroom door. Have two other students (perhaps large, athletic students) stand shoulder to shoulder in the doorway. Next ask the student in the hallway to come into the classroom. Of course the student will have to push the two students who are blocking the doorway out of the way. Explain that the student entering had to move mass out of the way to enter and that the student's "pressure" (*i.e.*, pushing) was the means by which the blocking students were moved. Since there was force and motion, there was work done by the entering student on the blocking students. Admittedly, this is not an everyday analogy in the traditional sense, but it is a familiar analogy when used in the context of an exclusive night club. Somebody that is not on "the list" may try to push past bouncers into the barroom – a familiar gag in the movies.

Dimensional analysis is not exclusively a fluid mechanics topic, but it is typically first introduced in a fluid mechanics course. When introduced to the student, dimensional analysis is described as "a packaging or compacting technique used to reduce the complexity of experimental" or analytical investigations "and at the same time increase the generality of experimental" or analytical information.[7] This of course is still just a jumble of words to the student – merely a definition. Further it may be explained to the student that dimensional analysis does not provide a final answer to an inquiry/problem; "it simply leads to a more efficient organization of the variables." Further still, dimensional analysis "suggests possible ways that the organization [of variables] can be carried out; however it does not allow us to find unique results." By now the student may be thoroughly confused where the instructor is going with this. Simply putting the definition of a Reynolds number on the chalkboard will not convey what dimensional analysis is and what it is used for. One of the present authors formulated two analogies in his textbook to

> *"help illustrate the utility of dimensional analysis. Dimensional analysis is similar to a trash compactor. Trash thrown into the compactor is crushed into smaller space so it is easier to handle. The compactor does not solve the trash problem nor does it ultimately dispose of any trash put into it; it only reduces it to a more convenient package. In the same way, dimensional analysis reduces the number of variables that* [the student] *must consider in an analytic or experimental investigation by "compacting" several of the raw variables into convenient packages".*[7]

Dimensional analysis will not solve the problem, only bring some organization to make the solution less tedious and more general..

"Dimensional analysis also is similar to packing a suitcase for a trip. The traveler must select the items to take. Two travelers to a similar destination may even select some different items depending on the objective of the trip. Any item that is not selected will not be in the suitcase. The traveler can organize the items in the suitcase in one of several equally convenient ways. Different travelers prefer different arrangements [especially if each choose different items], *but that does not make any arrangement superior. After the suitcase is packed, it is up to the traveler to carry it to the ultimate destination. The suitcase does not go on its own, and just packing it does not accomplish the objective of the trip.*[7]

An interactive classroom technique to use with this suitcase analogy is to select a male and female student from the room. Tell them they are individually packing for a trip to Hawaii. Ask them to list of a few of the items that they would be taking. Undoubtedly the male and female will be taking different items. Ask them how they would pack them. Most likely differently. Neither packing method nor list of items is superior to the other, but both will go to a similar destination, albeit with different objectives.

It should be noted that the "suitcase analogy" applies mostly to forming dimensionless variables by the Pi-Product method, wherein by choosing different repeating variables, different analysts will arrive at different sets of dimensionless variables or with different forms of familiar variables. A particularly common example of the latter is the fact that the Pi method usually produces $\frac{\mu}{\rho V \ell}$ instead of the much more familiar Reynolds number $\frac{\rho V \ell}{\mu}$.

3. Thermodynamics

Early in the course (and perhaps again in fluid mechanics) when discussing fluid properties, the instructor will discuss density. A warmer fluid is less dense than a cooler fluid. Therefore, in mid-summer the air is less dense than in early spring, assuming humidity levels are the same. Lower density will imply that less fluid mass will encounter an object in the flow. A quick sampling of baseball team homeruns in April/May 2010 compared to July/August 2010 shows that the average team hit approximately three more homeruns per month in mid-summer than in spring.[8] And this is not accounting for potentially higher humidity in the summer. The ball can fly farther in the summer with lower air density, so more long fly balls will become homeruns. (A further check of baseball statistics could also yield a comparison of long fly-outs per team and homerun distances, presumably further in summer than spring.)

Entropy and entropy generation caters very easily to everyday analogies. "The extension of the entropy concept to nontechnical fields is not a novel idea. It has been the topic of several articles, and even some books."[9] In Çengel and Boles popular Thermodynamics textbook, *Thermodynamics: An Engineering Approach*, an entire subsection is devoted to entropy and entropy generation in daily life with eight analogies ranging from armies to libraries to verbal outbursts. Entropy analogies are not difficult to find. With that said, it may be very instructive to use an entropy analogy involving the classroom; after all, the topic is being taught in a classroom. Ask the students to look around the classroom and describe the setting. They will see chairs, textbooks, paper, pencils and pens, laptop computers, handheld devices, calculators, book bags, purses, jackets, etc. strewn all over the place. Now ask them what the room looked like when they entered. Likely the chairs were arranged one per table-place and everything was generally neat and tidy. To measure the current disorganization would require some parameter, and entropy is the parameter that measures disorder. Further, the books and papers and general clutter will not return themselves to the book bags and to the dorm rooms. The process to return the room to the original state will require the expense of work from the students; they will need to burn some calories and give off some heat. In other words, the process cannot be undone unless an impact is given by or felt by the surroundings which only increases the entropy; in other words, the process is thermodynamically irreversible.

4. Heat Transfer

In transient heat transfer, the lumped capacitance method (or “lumped heat capacity method” or simply “lumped system analysis”) is considered the easiest. As a reminder, lumped capacitance can be used to solve a transient heat problem “by assuming the internal thermal resistance of a [body] is so small that the temperature” is considered uniform throughout the body at any given instant, and the external thermal resistance between the surface and the surroundings is large compared to the internal resistance allowing the external heat transfer to control the heat transfer.[10] Quantitatively, the calculation of Biot number is the guide, and if it is less than 0.1, or the internal resistance is less than 10% of the external surface resistance, lumped capacitance is considered a good assumption. To the student, understanding this explanation and when lumped capacitance is applicable can be initially difficult. Ironically the name itself is an analogy. The thermal lumped capacitance method “is analogous to the voltage decay that occurs when a capacitor is discharged through a resistor in an electrical RC circuit….This analogy suggests that RC electrical circuits may be used to determine the transient behavior of thermal systems. In fact before the advent of digital computers, RC circuits were widely used to simulate transient thermal behavior.”[11] For the electrical analogy to be useful, the student would need a firm understanding of electrical circuitry – an understanding often lacking in Mechanical Engineers, so presented here is an everyday analogy. Ask the students to imagine a very small sphere, a BB, made of copper at room temperature. Place it in your oven preheated to 400ºF. Ask the students if it would be fair to assume that as the copper BB heats, the temperature at the surface of the sphere is nearly the same as the temperature of the center of the BB. The authors typically get a split vote. Ask for an explanation why some students believe the assumption is good. They will likely mention three observations: the material has a low thermal resistance, the volume is small, and the shape is uniform. All of these lead to the conclusion that the assumption is good. The copper BB will heat to 400ºF relatively slowly, while the internal temperature can be assumed uniform during the process. Next have the students image a large roast beef placed in the same preheated oven (or better yet, imagine the Grinch and Cindy Lou Who down in Whoville placing the Roast Beast in the oven). Now the student knows that it will not cook uniformly from the surface to the center. In fact that is what makes roast beast so tasty – slightly crispy on the outside and soft and juicy in the middle. The material, size, and shape all worked against lumped capacitance validity. (Note here that Çengel has also used a similar analogy in his textbooks on heat transfer. In addition, he includes an analogy relating an island with incoming boats and an inland bus system to lumped capacitance.[12] An analogy similar to Çengel’s can be formulated in terms of a large, spacious room with a low number of small doors; it is easy to circulate inside but difficult to get in or out.)

When the lumped capacitance approximation is not satisfactorily accurate, a numerical method featuring dividing the physical object into finite "chunks" and marching the solution forward in time is often used. Such methods are invariably taught to students in an introductory heat transfer course. An important concept in such numerical methods is that of stability. It is well known [11, 13] that using an explicit numerical method, with all heat conduction and boundary heat transfer terms evaluated at the "old" time level, is much simpler than an implicit method with such terms evaluated at the "new" time level. Unfortunately, one must assure that the time step used not be too large else the calculations will become unstable as they are marched forward in time. This instability and its cause and consequences can be illustrated with a bathtub analogy.

At the beginning of the lecture period, say something like this: " Imagine that you have come home from a long day of studying and need to relax. A hot bath is just the thing. Imagine that you go into your bathroom, put the stopper in the tub drain, and turn on the hot water. While the water runs, let's do a little heat transfer." At this point, begin the lecture for the day; it will likely involve derivation of algorithms for numerical time-marching solutions to transient problems. It is of course easy to demonstrate that the explicit formulation is much more simple to execute than an implicit or semi-implicit formulation. Perhaps the instructor would ask the students which they would prefer to use – the answer is usually the explicit method, especially if they are told that neither method is inherently more accurate. Next, the instructor does an example of an explicit time marching calculation. The current authors prefer using a spreadsheet as it is easy to set up and the students can easily follow as the calculations are done. First, run the example with a small (stable) time step. Then rerun with ever increasing time step size. Eventually, a time step is reached for which the calculations blow up (*i.e.*, the stability limit has been exceeded). Ask the students why this might happen. As some begins to attempt an answer, the instructor feigns a state of great alarm and says something like "OH My Gxxxx! (Generally acceptable forms of Gxxxx are Gosh, Golly, or Goodness.) What has happened in that bathtub? It has been running all this time." Of course the students will understand that the bathtub has overflowed and that bad things are likely to result. The instructor then points out that that is exactly what has happened in the heat transfer calculations – the heat flow was turned on at the beginning of the time step and was left to run at the same value for the entire time step. If the bathtub is too small or the time step too large, one attempts to put more water in the tub than physically possible, and that is exactly what has happened in the heat transfer calculation – either the element was too small or the heat flow went on for too long a time. At this point, the stability criterion can be introduced as formally or informally as desired – the students understand in a physical way why a limitation exists.

Throughout Thermodynamics and Fluid Mechanics coursework, the concept of efficiency has been reinforced over and over. Every student knows that efficiency has something to do with minimizing the expenditure of costly resources. Later when a student is learning heat transfer, efficiency is typically not a practical or useful concept in the study of heat exchangers; effectiveness is a more proper measure of performance. Because the word "efficiency" looks a lot like and even sounds a lot like "effectiveness", students continue to confuse the two. A simple explanation of heat exchanger effectiveness is often not helpful enough to distinguish the difference: heat exchanger effectiveness is the ratio of actual heat transfer to maximum possible heat transfer. So how is effectiveness different than efficiency? An analogy involving college students can aid in answering that question. Consider two college students independently studying for an exam; each student has an entire day that can be used for studying. Student X studies for three hours and ultimately earns a B- on the exam. That was fairly efficient – small amount of resources (time) was used for an acceptable grade – but not necessarily very effective as the desired outcome is an A. Student Y studies for ten hours and ultimately earns an A on the exam. That is very effective but could be viewed as inefficient. In this scenario, the amount of resources used is not so important as each student had an entire day available. The important thing is getting to the desired outcome. In the same manner, efficiency is not a worthwhile measure when, say, comparing parallel and counterflow heat exchangers at the same operating conditions. The ultimate goal is to exchange as much heat as possible (and the counterflow heat exchanger will win).

5. Any Thermal-Fluids Course

Throughout thermal-fluids engineering, we are concerned with conservation laws; most commonly conservation of mass and conservation of energy. A factory makes for a good analogy for either of these conservation laws. Standing at the entrances to the factory are employees (or even better, co-ops or interns) with clipboards. They are taking inventory of all the raw materials that go in. At the exits from the factory are other workers with other clipboards. They are monitoring everything that is going out. Now what comes out may be in a different form than what went in, but it is still composed of the raw materials that entered. If at the end of the day, the entrance employees compare their clipboards with the exit employees, the factory manager will know if the stock inside has increased, diminished, or remained equal. So the clipboard employees are monitoring what happens at the boundaries, and the operations in the factory can also be observed, but don't need to be. In this analogy, it might be helpful to work in a phrase popular in old west movies: "I saw the varmint go in there and he ain't come out, so he's still there".

6. Conclusion

Most analogies seem to pop into mind when you are not actively seeking one, so unfortunately, there are few guidelines on creating your own. Subconsciously be on the look-out for analogies during your everyday activities or even when watching movies or television. Often the most poignant analogies are those that relate directly to the college student or student life.

When creating analogies, follow a few simple guidelines. First the analogy does not have to be a perfect match, but if there are glaring inconsistencies, omit that part of the analogy or do not use it at all. A mismatched analogy will only create an impaired visualization of the reality of the course topic that will be difficult to erase from the student's mind. Keep the analogy relatable and familiar. They must pertain to the average student or there is no value in the analogy. Certainly there will be the occasion when one or two students have no idea what your analogy is; this is common with some foreign students that have not long been immersed in American culture. That is OK as long as the majority of the students can relate to the analogy. Finally, if possible, keep the analogy interactive, perhaps through question and answer. You could even have students "think-pair-share." In other words, ask a question, have the students think about it, turn to a neighbor to discuss, and share their answers.

Familiar analogies are more than just a teaching tool for difficult-to-grasp concepts; they are also a moment to break the monotony of technical material and a chance for the students to redirect their attention or even bring back their attention. Using them is enjoyable for the instructor and the student. Lastly, when you come up with useful and/or fun analogies, feel free to share them with your colleagues and the authors.

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