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Synopsis:

Convective heat transfer does not conform to the definition of heat transfer, i.e., the driving force is solely by temperature difference. Convection as a mode of heat transfer presents confusion and impedes learning. Improper teaching propagates through society; therefore, properly educating our future STEM professions is important. This paper presents a new teaching model for visualizing convective heat transfer.

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Abstract

Statistics show that many students are not going into the practice of engineering after graduation from college, and in recent years, there has been a significant decline in the number of high school and college students choosing majors in engineering professions. The United States government has investigated these statistics and initiated a campaign under the name of Science, Technology, Engineering, and Mathematics (STEM) to improve higher education and to prepare and inspire students in these areas. The purpose of this paper is to present a conceptual model for teaching convective heat transfer to college undergraduates and high school students in technology schools. The Boxcar Model provides a clear way of understanding and visualizing convective heat transfer concepts rather than the classical engineering approach, which may be difficult for and intimidating to some students to understand. This paper discusses traditional convective heat transfer, compares the classical teaching approach of convective heat transfer and the Boxcar Model. In addition, the paper uses two types of heat exchanger devices to explain the conceptual model and the use of the model in the classroom.

Introduction and Motivation

Technical jobs in the science, technology, engineering, and mathematics (STEM) play an instrumental and critical role in expanding scientific and technological progress and development in the United States and the world. The United States Department of Labor (DOL) reports that total employment in the strictly defined science and engineering disciplines will increase by 20.6% from 2008 to 2018, a rate that will increase more than double the overall growth rate compared to other occupations[1,2]. The growth rate for all jobs from 2008 to 2018 is approximately 10.1%. Specifically, the engineering occupations have a growth rate of 11.3% for the same range, slightly more than all jobs[2]. In contrast to this growth rate, future trends in the number of science and engineering (S&E) positions will exceed the general workforce requirements by more than four (4) times the annual growth rate of all occupations when using 1980 as a baseline [3].

Imperil to the United States' job prospects, the nation has a challenge to maintain enrollment in S&E programs at most of the colleges and universities, as well as holding the interest of undergraduate student in the S&E fields. In other countries, the retention and undergraduates degrees in the natural science and engineering range from 38% to 67%, while in the United States the number is 15%[4]. Clearly, if the United States is to continue employing science and technology as an engine of economic growth and national security via an ample and well-educated workforce, it will need to maintain global competition for S&E talent and increase the number of native-born S&E graduates.

The overarching motivation of this paper lies in the reasons of declining enrollment and retention in many of the STEM programs, specifically engineering. Many students are often turned-off by the way these subjects are taught, e.g., traditional classroom lectures of classical theories, seemingly meaningless laboratory experiments, and minimum real world problem solving. Therefore, to attract and retain more students into STEM careers, technology high schools, colleges, and universities must provide meaningful and useful learning experiences that motivate and excite the students - learning experience that relates directly to the practice of the specific STEM career. For example, after teaching a heating, ventilating and air-conditioning (with practical design and analysis) course, a student stated (paraphrased), ' After five years of engineering school, this is the first time I felt like I did real engineering.' The course uses real design drawings and calculations to size cooling and heating equipment, e.g., chillers, boilers, valves, steam traps, ductwork, and appurtenances. Therefore, STEM educators must be capable of

- relating real world experience to classroom teachings,
- challenging students to "think out of the box",
- apply student new learned knowledge, skills, and abilities to authentic real world problems,
- build and refine theories and models,
- relate engineering problems and explanations to practical conceptual models, and
- use specialize and creative ways of talking, writing, and representing phenomena.

In concept, the results of providing this type of learning experience will prove beneficial to the instructor and student.

Classical Approach to and Problem with Convective Heat Transfer

Before delving into the Boxcar Model, it is helpful to discuss the classroom teaching of convective heat transfer from the traditional point of view. Espinola states " The study of convection suffers from many complications not the least of which is that convection is not really a form of heat transfer but is, rather a form of mass flow energy transport.[6]" He adds convection to his book only because it is traditionally considered a heat transfer mode. Jakob emphasizes that the convection phenomenon does not need a special and new formula (Equation 1.3) because it is a case of heat conduction.[7]

$$Q = h * A * (\Delta T) \qquad \text{Equation 1.3}$$

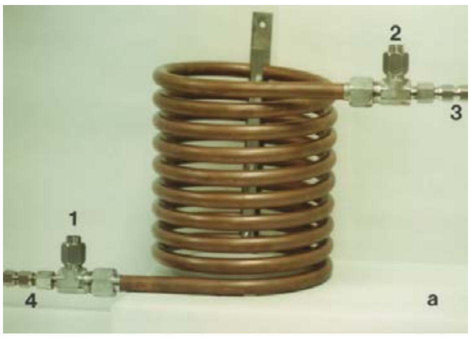
The laws of heat transfer and fluid dynamics govern heat conduction, complicated by flow of the fluid. Therefore, in theory, it is possible to avoid Newton's Law of Cooling entirely, and develop any problem of heat transfer without using the heat transfer coefficient, h. To resolve the confusion one must revert to the definition of heat transfer, i.e,

"Heat transfer is the study of energy transfer solely as a result of temperature difference.[8]"

Convection heat transfer does not comply with this definition because the phenomenon involves the functionality of variables such as velocity or time, orientation, geometry, surface condition, temperature difference[9], and possibly others variables. Then, what is convection? Convection was a term used in the 1600s and 1700s to explain the transfer of heat from a solid surface to a fluid. However, the energy transfer is actually due to conduction with some contribution from radiation – at low temperature. Convection can be explained qualitatively in terms of conduction. For instance, convection is a series of conduction and radiation energy. The flow conditions distorts and retards the energies, similar to heat going through fluids communicating the effects to the ambient fluid little by little, and communication causes the heat to lose its own motion (heating effect). Hence, retardation and distortion of heat in the fluid is proportional to the motion communicated. In other words, the velocity of the fluid in a specific geometry of flow retards or distorts the magnitude of heat transferred to the fluid. This explains the inefficiency of the fluid to use its full potential capacity because of the fast resident time or velocity; hence, limiting energy to the center fluid layer. In general, the energy in moving fluid consists of mechanisms relating to conduction, radiation, mixing (with and without turbulence), and transport of mass. Convection is not a heat transfer mode; it is merely the energy transport of conduction and radiation via fluid motion. The concept is similar to the transport of turbulence or advection via pressure, viscosity, and shear stress. As one can see, the detail of convective heat transfer is difficult to understand and the concept can be intimidating for students, which can be a turn-off.

Heat Transfer Straight and Coil Tube Models

To show how the Boxcar Model works in the classroom, let us consider a model of a coil and straight tube heat exchanger (Figure 1). Both devices consists of the same size copper tubing, identical velocity with the same fluid inside the tube, and the level of heat surrounding the tube. If one examines the straight tube, it is obvious that the temperature profile of the inside fluid would look like Figure 2 at constant heat and velocity in the turbulent (Figure 2.B) and laminar (Figure 2.C) range.



(a)

(b)

Figure 1: (a) Coil tube   (b) Straight tube

The ideal conditions would look like Figure 2.A, indicating that the fluid has acquire the maximum heat; hence, this is what researchers and engineers strive to accomplish to ensure full utilization of the fluid in motion to satisfy the end user. If the flow is in the turbulent regime, it approached full utilization of the fluid due to mixing because of the fluid and the wall interaction that causes swirling. Nevertheless, the temperature profile further improves by change the tube from straight to coil or spiral.

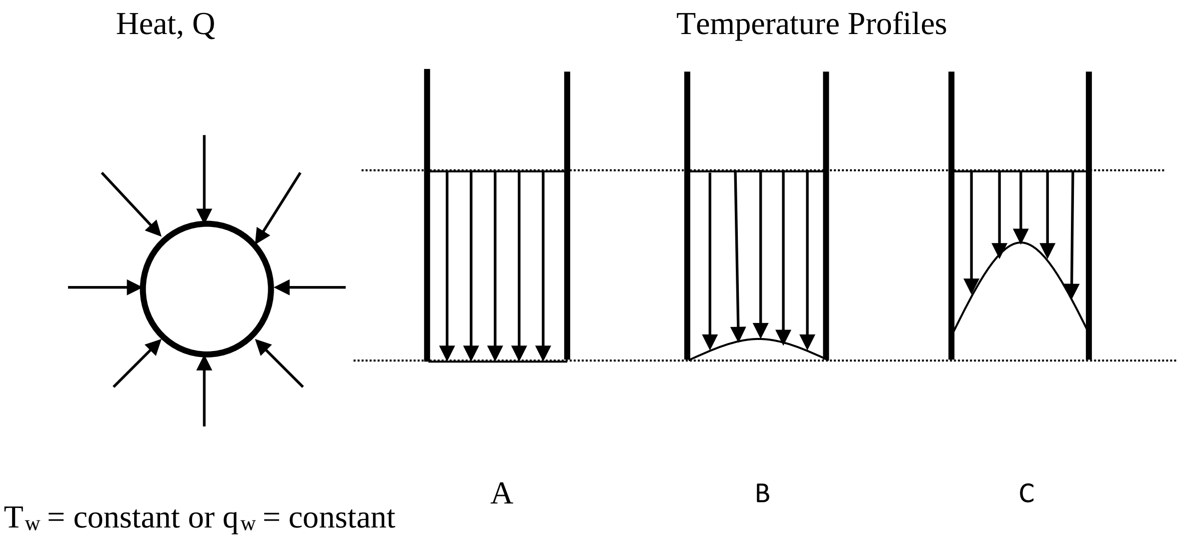


Figure 2: Tube temperature profiles with changing velocity.

The coil device allows the elements of fluid to interact with heat for a longer time. Furthermore, the swirling action of the fluid within the coil tube induces additional mixing. Hence, obtaining additional heat that makes the fluid approach saturation, assume no phase change. The Boxcar Model explains the process that increases the fluid utilization to maximize heat absorption.

Boxcar Model used to Teach Convective Heat Transfer

The present day convective heat transfer model improperly addresses how heat transfers to the fluid. The majority of the unknowns are lumped into the heat transfer coefficient, h (or Nusselt number, Nu). As seen in Figure 3, the proposed Boxcar Model views the heat input (sand loading) and transport (boxcar shipping/switching) as separate but related actions. The moving boxcar models the transport action of sand (or heat), which represent the fluid in motion. The falling sand from a group of silos is analogous to the heat-input action, i.e., loading. The amount of substance/sand (or heat) in each boxcar (or segment of fluid) is a function of how fast the boxcar (fluid) moves, how fast and how much of the substance/sand (or heat) loads-in from the chute of the silo (crossing the open plane of the boxcar), and how large (capacity) is the boxcar. One can readily visualize the amount of heat getting into the fluid if one thinks in these terms. For example, if a condition exists for constant loading of sand from the silo and for varying speed of the boxcar, then the amount of sand deposited into the boxcar varies. Hence, the key to optimum or maximum deposition is to balance the loading rate of sand and the boxcar velocity and capacity.

In addition, this involves geometric parameters of the boxcar as well as the medium of material that the substance passes through before crossing the top of the open boxcar. For example, the effects of wind could make the transfer or deposition process less effective and cause the sand to deposit in places other than into the boxcar. This is similar to fouling scale (i.e., hardness minerals) buildup on the wall of heat transfer tubes; hence, impeding effective heat transfer. Based upon a steady state and balanced condition of sand loading and boxcar speed, the capacity of the boxcar becomes more effective and the controlling factor in the process. Comparing this concept to Newton’s Law of Cooling, this visualization may not be readily apparent because all the transfer and transport mechanisms are lumped into the heat transfer coefficient. However, if we look at convection in the context of conduction, the concept becomes apparent. The phenomenon of mixing is also apparent. With respect to mixing, one would have to model the operation that takes place at a train-switching yard, or station with intercepting rails.

Referring to Figure 3, the boxcars levels switch places in a systematic way, which leads to maximum and uniform sand deposition. Without this switching, the boxcar utilization and the transfer of sand from a higher to lower elevation becomes inefficient and ineffective. The effectiveness of the boxcars to contain a maximum amount of sand is analogous to the thermal capacitance of the moving fluid. The key to good heat transfer is to ensure all the fluid sees or absorbs the same or maximum amount of heat. Hence, the Boxcar Mod Model conceptually represents how heat conducts, absorbs, and transports to moving fluids. Table 1 shows the relationship between the physical heat transfer system and the conceptual Boxcar Model.

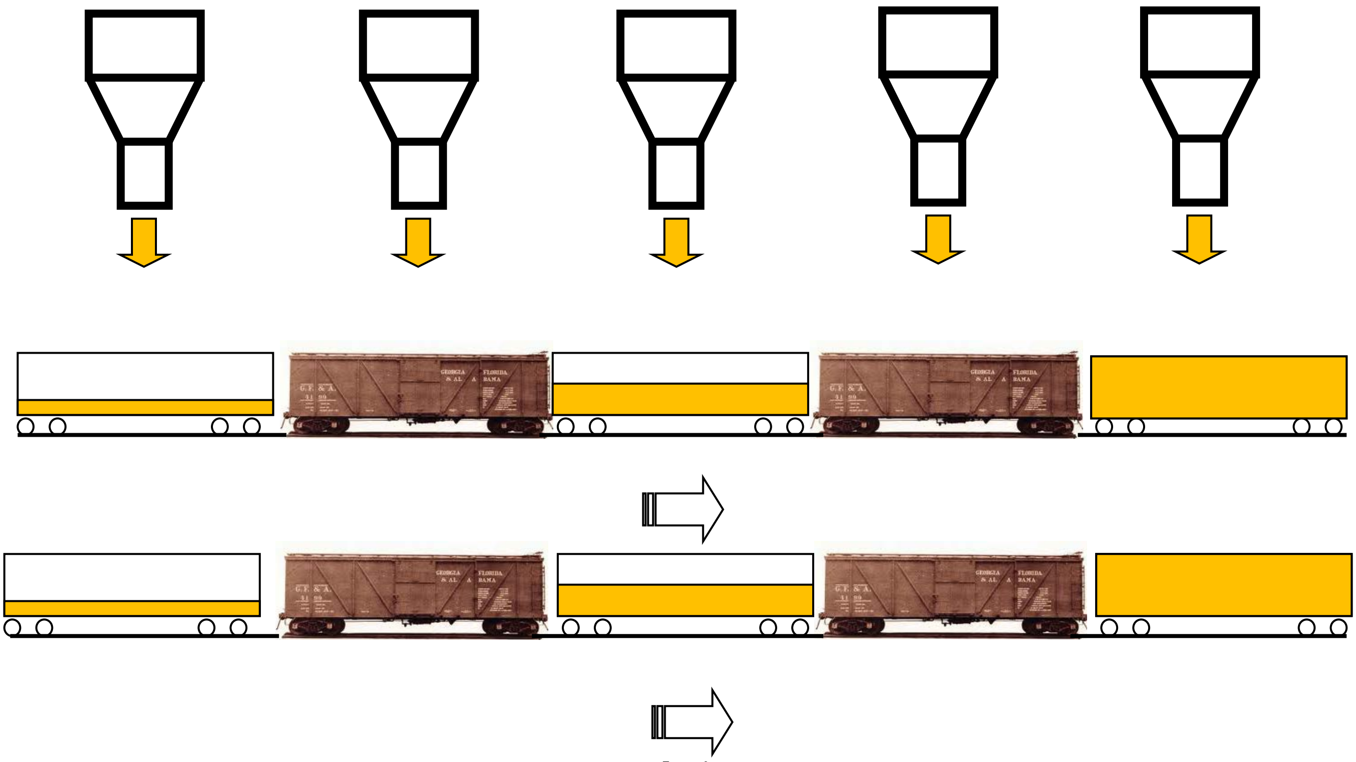


Figure 3: Boxcar Model Concept

Table 1: Convective Heat Transfer system verses Boxcar model.

Heat Transfer Physical System	**Boxcar Model Conceptual System**
Heat, Q (Energy Form)	Sand, m (Mass Form)
Fluid Levels/Segments	Train or Boxcar Series
Wall Conduction	Loading through Silos
Transport of Energy	Shipping of Sand
Heat Capacity	Boxcar Size
Fluid Velocity	Train or Boxcar Speed
Heat Transfer Area	Number of Loading Ports
Mixing of Fluid	Switching of Trains/Boxcars
Turbulence	Large-scale Switching
Surface Tension Effect	Slow and Static Boxcars

Conclusion

The proposed conceptual Boxcar model provides a simpler and clearer explanation for the process of convective heat transfer. The Boxcar model gives a visualization of the actual process; hence, making it easier for students to grasp the heat transfer concept. As a teaching tool, the Boxcar model provides an effective way of communicating and teaching convective heat transfer to practicing engineers and students in science and engineering. The Boxcar Model presents a conceptual methodology to understanding and improving convective heat transfer processes and devices.

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