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A DISCOVERY-BASED CASE STUDY TO TEACH THE CONCEPTS OF COMPUTATIONAL SIMULATION AND MEASUREMENT UNCERTAINTY IN HEAT TRANSFER

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Abstract: The present study was used to teach undergraduate students the concepts of computational simulation and measurement uncertainty via discovery based learning. The study included experimental-theoretical-numerical examination of heat conduction along a cylindrical rod. Because it is a well-known fact that dealing with systems having complex theoretical background distracts students' attention, an easy to be comprehended experimental system had intentionally chosen to allow the students mainly focus on the computational simulations and measurement uncertainty. Students were requested to compare the results obtained at each step and to figure out the possible causes of discrepancies among the results if there was any. The steps were repeated several times until the students satisfied with the results.

Keywords: Conceptual model, uncertainty propagation, simulation-based engineering

Isı Transferinde Bilgisayar Destekli Simülasyon ve Ölçüm Belirsizliği Mefhumlarının Keşif Tabanlı Örnek Vaka Aracılığı ile Öğretilmesi

Özet: Bu makalede lisans öğrencilerine bilgisayar destekli simülasyon ve ölçüm belirsizliği kavramlarını proje tabanlı öğrenme usulü ile öğretebilmek için kullanılan bir çalışma anlatılmıştır. Çalışma silindirik bir çubuk üzerindeki iletimsel ısı transferinin deneysel, teorik, numerik incelenmesini içermektedir. Öğrencilerin karmaşık teorik altyapıya sahip sistemlerle ilgilenmelerinin dikkatlerini dağıtacağı iyi bilinen bir gerçek olduğu için teorik altyapısı rahatlıkla anlaşılabilecek deneysel bir sistem kasıtlı olarak seçilmiştir ki bu sayede öğrencilerin dikkatlerinin bilgisayar destekli simülasyonlar ve ölçüm belirsizliği konuları üzerine yoğunlaşmaları hedeflenmiştir. Öğrencilerden her bir adımda elde ettikleri sonuçları bir diğeri ile karşılaştırmaları istenmiş ve varsa birbirleri arasındaki sapmaların muhtemel sebeplerini ortaya çıkarmaları beklenmiştir. Her bir adımın öğrenciler sonuçlardan tatmin oluncaya kadar tekrarlanması sağlanmıştır.

Anahtar Kelimeler: Kavramsal model, belirsizliğin yayılması, simülasyon tabanlı mühendislik

1. INTRODUCTION

For the last two decades the rapid progress in computational power and programming has substantiated the importance of integrating computational simulations in engineering curriculum (Kassim and Cadbury, 1996; NSF Report, 2006; Sert and Nakiboglu, 2007; Dahm and Hesketh, 2008; Stamou and Rutschmann, 2011). However, finding proper, efficient, and motivational

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way to teach undergraduate students the basis of computational simulations is not that easy, since computational simulation of an engineering system requires a strong theoretical and practical knowledge of fundamental physical/chemical/biological principles as well as mathematical background of the engineering system of interest (Zamora et al., 2010; Moore et al., 2013; Cengel and Ghajar, 2015). In addition, some level of expertise in computer programming is also needed. Although the use of a commercial CFD package could ease the burden of coding and its verification, the students should still have proper conceptual and mathematical modeling intuition (Roache, 1997; Vazquez-Arenas and Pritzker, 2010).

Conceptual modeling is, maybe, the most important part of the simulation-based engineering in order to have a validated computational model at the end. Without developing a conceptual model of the system of interest, by building either a physical model (small scale physical model) or an imaginative model in modelers' mind, it is impossible to properly determine the governing mathematical equations, boundary and initial conditions (i.e. boundaries of the system), and assumptions, as well. In other words, to have a validated computational model, the right equations have to be solved under the right conditions and assumptions (Roache, 1997). Nevertheless, regrettably it is a common teaching experience that, even for a basic engineering system, it is very difficult to build an imaginative (conceptual) model in students' minds in the beginning.

Developing a reliable conceptual model needs several reiterations. It starts with the observation of the system of interest through the fundamental physical/chemical/biological knowledge. This follows the determination of possible sub-process controlling the system. The latter step helps modeler select proper mathematical equations governing each sub-process along with boundary and initial conditions needed to solve these equations. In addition, assumptions have to be made in order to expedite numerical solution process and to reduce the need for computational power (Magana and Coutinho, 2017; Magana et al., 2017).

Beginners (e.g. science and engineering students) generally think that using a computational simulation program is as easy as using a calculator, but when a problem arises while solving governing equations (e.g. non-converging solutions) they become puzzled and realize that without knowing how to do simple arithmetic calculations it is not possible to use a calculator. Although their first failure is good for breaking their bias, it impairs their motivation for learning. For this reason the lecturers have been trying to find motivational and efficient ways of teaching the theoretical and practical foundations of computational simulations of engineering systems (NSF Report, 2006; Magana et al., 2017; Zhou and Wang, 2016).

The theoretical foundations of computational simulations can be related to, but not limited to, fundamental engineering courses such as physics, differential equations, numerical methods, fluid mechanics, heat and mass transfer. And without theoretical knowledge one cannot properly construct pertinent computational geometry, associate appropriate governing mathematical equations (as well as boundary and initial conditions) of physical phenomenon with the geometry, assemble suitable mesh system for obtaining convergent and satisfactory solutions. In addition to strong theoretical background, an experimental model is also essential for developing students' imagination of the physical/chemical/biological processes involved in a real system in order to help them translate abstract science terms into pictures of reality (Cengel and Ghajar, 2015).

Moreover, students should also be aware of possible error sources encountered in experimental measurements since the offset-parameters used in the theoretical models/calculations and numerical simulations are based on these (Guisasola et al., 2006; Cengel and Ghajar, 2015). Even in well-controlled measurements uncertainties are always present and they have to be chased in order to avoid any unanticipated uncertainty propagation in the theoretical calculations and numerical simulations. Especially in heat transfer studies there may be noticeable uncertainty found in the data (e.g. 15% uncertainty in the convectional heat transfer coefficient is not considered "exceptional") (Cengel and Ghajar, 2015). This being the case, it is very important for students to grasp the concept of measurement uncertainty (Chimeno et al., 2005; Guisasola et al., 2006; Jalkio, 2011; Batstone, 2013; Cengel and Ghajar, 2015).

However, for the beginners, it can be quite difficult to perceive the concepts of computational simulation and measurement uncertainty. This is why educators have been sought efficient ways of teaching these concepts. Among the tested ways of teaching, discovery based learning may be the most promising one; since students seek for their own answers while learning new scientific concepts and tools by integrating theory and practice (Finlayson, 2007; Arslan, 2009; Hillard et al., 2015; Chen et al., 2016).

Thus the aim of the current study was to present an introductory level case study to teach undergraduate students the concepts of computational simulation and measurement uncertainty by discovery based learning. A simple but highly regarded (Gvirtzman and Garfunkel, 1996; Abu-Mulaweh, 2005; Abu-Mulaweh and Mueller, 2006; Stammitti, 2013) heat conduction experimental system was chosen in order to prevent students from overwhelming with the theoretical background and to let them only focus on the conceptual model development and identifying possible reasons for inconsistent results. Along with learning the new concepts in engineering, students would have the advantage of learning using COMSOL (version 5.2) and a spreadsheet program.

2. METHODOLOGY

2.1. Approach and Goals

It should be stated that the method used in the current study had already implemented in a junior level elective course (ESM 324 - Modeling of Engineering Systems) at the department of Energy Systems Engineering (University of Yalova, Turkey) for the last five years. The positive feedback from the students had encouraged presenting the study as guidance to our colleagues. It was believed that the current paper would act as a good starting point for the lecturers seeking for a pre-tested and detailed source for teaching the concepts of computational simulation and measurement uncertainty in their engineering courses along with the usage of one of the most notable computer simulation software.

It is advised that introductory level knowledge of numerical methods, differential equations, heat transfer may be useful for the prospective students.

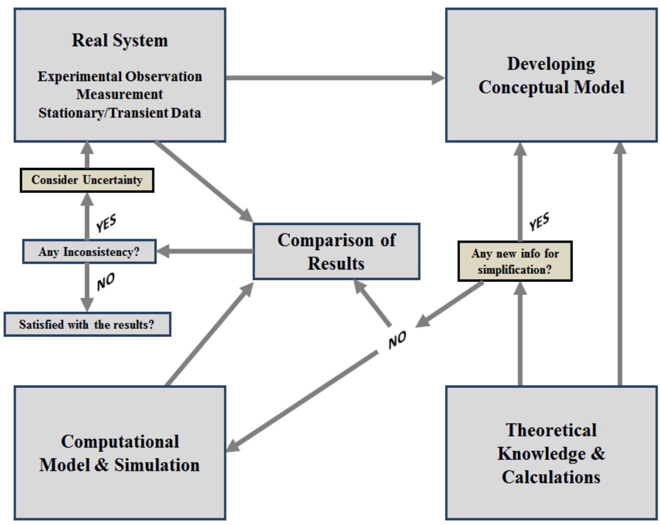

Figure 1:
Flow chart showing five interrelated steps involved in the study

The teaching method consisted of five interrelated steps (Figure 1). As a first step, the temperature profile along a cylindrical metal rod (with constant cross-sectional area) was experimentally measured with an educational heat transfer experimental set by Edibon International (TXC/SE) (Madrid, Spain). It should be noted that in the beginning, students were not warned about possible sources of experimental errors and uncertainties stemming from instruments used in the experimental measurements. Then the students were asked to develop a representative (conceptual) model of the experimental system. Virtually all of them agreed on a three-dimensional geometric model. Third step involved the calculation of temperature profile on the rod by the equations given in the textbooks utilizing a spreadsheet program. While calculating the temperature profile the students were appeared to become aware that the heat conduction along the rod with constant cross-section could be investigated one-dimensionally. On the fourth step, two-dimensional simulation of heat conduction on the rod was demonstrated with COMSOL Multiphysics® (version 5.2).

At the end when the experimental, theoretical, and numerical results were compared with a spreadsheet program to demonstrate whether the results deviated from each other. The students were surprised that the experimental results deviated from the theoretical and numerical results. Then they were briefly instructed on the uncertainties in the measurements and how they propagate in the calculations and affect theoretical and numerical input parameters. After the deviation due to uncertainty propagation had been added to the graphic as error bars, the students was surprised to discover that even in a purely one-dimensional heat transfer process uncertainty propagation could have unanticipated effect.

2.2. Theory

2.2.1. Experimental Set-up

The experimental apparatus was acquired from Edibon International (TXC/SE- Extended Surface Heat Transfer Module). The cylindrical brass rod covered with black paint had a diameter of 0.01 m and a length of 0.327 m. The experimental setup is depicted in Figure 2.

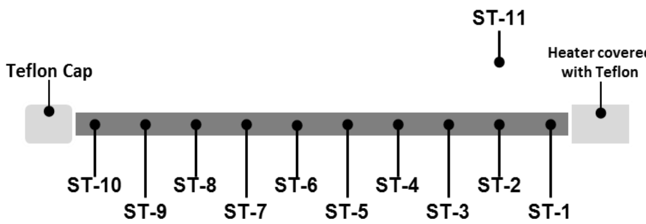

Figure 2:
The experimental set-up

The thermocouples (T-type) used to measure temperatures on the rod were labeled with numbers starting with ST1 which was the closest thermocouple to the heated base. And ST-10 was the closest one to the tip of the rod which was insulated with a white Teflon cap. The rest of the thermocouples were located on the rod with 3 cm intervals. Due to technical difficulties encountered in the experiment the temperatures measured by ST-1 and ST-9 were not included in the results. ST-11 was used to measure ambient temperature in the room. The exact locations of the thermocouples are given in Table 1.

At steady state conditions the base (T_b) and the ambient air (T_∞) temperatures were 57.4°C and 20.5°C, respectively. The tolerance ranges in the temperature and length measurements were ±0.75% (given by Edibon, Inc.) and ±0.5mm, respectively.

Table 1. The temperature distributions found with all techniques

Thermocouple Number	x (meters)	Experimental (°C)	Theoretical (°C)	COMSOL-2D (°C)
ST-2	0.045	47.90	46.95	46.95
ST-3	0.075	44.88	41.75	41.75
ST-4	0.105	40.50	37.66	37.65
ST-5	0.135	36.88	34.44	34.44
ST-6	0.165	33.70	31.95	31.94
ST-7	0.195	32.18	30.04	30.04
ST-8	0.225	29.23	28.63	28.63
ST-10	0.285	27.70	27.01	27.01

2.2.2. Theoretical Calculations

For fins with uniform cross sections and adiabatic (insulated) tips the following Equations (1)-(2) was used to calculate temperature profile along the fin (Cengel and Ghajar, 2015) with the following assumptions:

- One-dimensional conduction in the x-direction,
- Steady state conditions,
- Uniform thermal conductivity,
- No heat generation,
- Constant and uniform convective heat transfer coefficient over the entire surface,
- Constant Temperature at the base.

$$T(x) = T_\infty + (T_b - T_\infty) \cdot \frac{\cosh[m \cdot (L_{rod} - x)]}{\cosh[m \cdot L_{rod}]} \tag{1}$$

$$m = \sqrt{\frac{h_{comb} \cdot P}{k_{rod} \cdot A_c}} \tag{2}$$

x: Location of the thermocouples on the x axis (m)

T_b: the base temperature (K)

T_∞: the room (ambient) temperature (K)

L: the total length of the rod (m)

P: the perimeter of the rod (m)

A_c: the cross sectional area of the rod (m^2)

k_{rod}: the thermal conductivity of the brass rod (110 W/m·K)

h_{comb}: the combined (convection + radiation) heat transfer coefficient (W/m^2·K)

Here it should be noted that the most important part of the theoretical calculations may be the calculation of the combined heat transfer coefficient (Abu-Mulaweh and Mueller, 2006;

Cengel and Ghajar, 2015). It is a well-known fact that the convection heat transfer coefficient strongly depends on the properties of the coolant (i.e. air) and the rod at a certain temperature. Moreover, if the fin's surface is painted in black, when the emissivity is unity, the radiation heat transfer rate could be added to the convection heat transfer rate to find the combined heat transfer rate (Cengel and Ghajar, 2015). With the combined heat transfer rate one can easily calculate the combined heat transfer coefficient which is also needed in the computational simulations.

2.2.3. Numerical Simulation

The simulations were done with COMSOL Multiphysics® (version 5.2), one of the commonly used commercial computational simulation program based on finite element analysis (Finlayson, 2007; Datta et al., 2013; Magana et al., 2017). The simulations of the temperature profile of the brass rod were done two-dimensionally (2D) to prevent students from any confusion associated with one-dimensional boundary selection in the program (i.e., a special boundary selection was needed heat to account for convectional heat loss from the surface in one-dimensional simulation) and to prove them that the three-dimensional simulation of the system was redundant. Although the two-dimensional simulations were done, for those who may want to include all dimensions in their courses, the domain and boundary properties associated with all dimensions were summarized in Table 2. Here it should be noted that for the two-dimensional and 2D axial-symmetric geometries the thickness of the rod should be entered as radius instead of diameter, since the heat conducts from the center of the rod to the surfaces radially in all directions. In addition, the cross sectional area and perimeter need to be entered in the 'heat transfer in solids (ht)' section for 1D case.

Table 2. The domain and boundary properties associated with all dimensions

Space Dimension	Geometry / Domain Type	Axis of the System	Boundary Type	Boundary Conditions
1D	Line / Interval Length=0.327 m	x	Point	Temperature + Out-of-plane Heat Flux (Domain Property)
2D (Current Study)	Rectangle / Surface Width = 0.005 m / Length=0.327 m	x,y	Edge	Temperature + Heat Flux
2D-Axial Symmetry	Rectangle / Surface Width = 0.005 m / Length=0.327 m	r,z	Edge	Temperature + Heat Flux + Axial Symmetry
3D	Cylinder / Volume Radius = 0.005 m / Length=0.327 m	x,y,z	Face	Temperature + Heat Flux

For the current study the boundary conditions and the parameters used in 2D simulations are given in Table 3. One can easily construct 2-D model of the system within COMSOL by following the steps given in Cakmak (2018a). In addition, the boundary conditions associated with physical tip conditions are given in Table 4 for those who may want to include the effect of different tip conditions in their courses.

Table 3. The boundary conditions and the parameters used in 2D simulations

Geometry	Parameters	Initial Conditions	Boundary Conditions
Rectangle	Heat Transfer in Solids	Initial Temperature of the rod	‘Heat Flux’ with convective heat flux on the elongated boundaries
Width = 0.005 m	Thermal Conductivity of the rod	T=20.5 °C	h=15.7 W/(m^2·K) T=20.5 °C
Length=0.327 m	k=110 W/(m·K)		‘Temperature’ on the heated edge T=57.4 °C
			‘Thermal Insulation’ on the tip

Table 4. The boundary conditions associated with physical tip conditions

Tip Condition	Modification on the computational model
Convection Heat Transfer	Heat Flux boundary condition on the tip
Adiabatic	Insulation boundary condition on the tip
Prescribed Temperature	Temperature boundary condition on the tip
Indefinite Fin	The length of the rod has to be long enough to ensure that the temperature on the rod gradually becomes equal to ambient temperature (T_s) as getting close to the tip.

The effect of mesh quality on the results was found to be negligible for 2D simulations (Table 5); this is why the number of elements on the boundaries was selected to be 50 in order to use computational sources efficiently otherwise students could encounter problems while using computers with lesser processing power. The details of constructing mesh system in COMSOL are described in Cakmak (2018b).

Table 5. The effect of mesh quality on the results for 2D simulations

Number of Elements on the boundaries	Total number of mesh elements	Temperature calculated on ST7 °C
5	25	30.038
50	2500	30.039
500	250000	30.039

After the solution, which did not take more than a second with computer that has Intel i7 CPU and 16 GB RAM, was ready, the results were exported to MS Excel for the comparison with analytical and experimental results.

2.2.4. Uncertainty Propagation in the Numerical and Theoretical Calculations

To find the uncertainties in the results calculated from measured values the following equations were used (Moffat, 1988; Holman, 2012):

If a calculated value R is the function of independent variables (x_1, x_2, x_3,…,x_n):

$$\mathrm{R} = \mathrm{R}(\mathrm{x}_1, \mathrm{x}_2, \mathrm{x}_3, \dots, \mathrm{x}_\mathrm{n}) \tag{3}$$

And the W_R is the total uncertainty in R:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \tag{4}$$

where (w_1, w_2, w_3,…,w_n) are the uncertainties in the independent variables (±0.75% for temperature and ±0.5mm for length measurements in the current study).

Step-by-step calculations can be found at Cakmak (2018c).

3. SOLUTIONS and RESULTS

The students were first examined the experimental system and they were instructed about steady state and transient responses of the systems. So they agreed to wait until the system reached steady state (approximately 115 minutes) before recording the temperatures measured with each thermocouple. While waiting for the system to reach steady state the students were briefly informed on the importance of the properties of the air at the film temperature (Equation (5)) and how to find these values from the tables given in the textbooks. The experimental analysis supplied the base and the ambient air temperatures (57.4 °C and 20.5 °C, respectively) at steady state conditions. Assuming air is an ideal gas at 1 atm, the film temperature calculated as following:

$$T_f = \frac{(T_b + T_\infty)}{2} = \frac{(57.4+20.5)}{2}$$
$$T_f = 38.95\ °\mathrm{C} \tag{5}$$

Because the properties of air at 1 atm does not change much between 35°C and 40°C the film temperature was taken as 40°C (from Table A-15 in Cengel and Ghajar (2015)). The convective heat transfer coefficient was then calculated from the Nusselt number which includes the Rayleigh number that is the product of the Grashof and Prandtl numbers:

$$Ra_D = Gr_D\, Pr = \frac{g\beta(T_b - T_\infty)D_{rod}^3}{\vartheta^2} Pr$$
$$Ra_D = 2913 \tag{6}$$

where g is the gravitational acceleration (9.81 m/s^2), β is the volume expansion coefficient (1/T_f in Kelvin for ideal gases), D_{rod} is characteristic length (the diameter of the rod in this case, 0.01 m), ν is the dynamic viscosity of the air (1.7 x 10^{-5} m^2/s at 40 °C), Pr is the Prandtl number (0.7255 at 40 °C) (Cengel and Ghajar, 2015). The Nusselt number used here has been recommended for natural convection from a long horizontal cylinder in a wide Rayleigh number range (Ra_D<10^{12}) (Churchill and Chu, 1975; Bergman et al., 2011; Cengel and Ghajar, 2015).

$$Nu = \left[0.6 + \frac{0.387 \cdot Ra_D^{\frac{1}{6}}}{\left[1+\left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right]^2 \tag{7}$$

$$Nu = 3.3$$

The convection heat transfer coefficient now could be calculated:

$$h_{conv} = \frac{k_{air}}{D_{rod}} Nu$$
$$h_{conv} = 8.8 \text{ W/m}^2\cdot\text{K} \tag{8}$$

where k_{air} is the thermal conductivity of the ambient air (0.02662 W/m·K).

And the convection heat transfer rate was found to be:

$$Q_{conv} = A_s h_{conv}(T_b - T_\infty)$$
$$Q_{conv} = 3.33 \text{ W} \tag{9}$$

where A_s is heat transfer surface area ($\pi \cdot D_{rod} \cdot L_{rod}$)

Then the radiation heat transfer rate was needed to find the combined heat transfer coefficient:

$$Q_{rad} = \epsilon \sigma A_s \left(T_b^4 - T_\infty^4\right)$$
$$Q_{rad} = 2.62 \text{ W} \tag{10}$$

where ϵ is the emissivity (unity), σ is the Stefan–Boltzmann constant (5.670 x 10^{-8} W/m^2·K^4).

$$Q_{comb} = Q_{conv} + Q_{rad}$$

$$Q_{comb} = A_s h_{comb}(T_b - T_\infty) \tag{11}$$

$$Q_{comb} = 6.0 \text{ W}$$

Finally the combined heat transfer coefficient (Equation 12) was calculated from the combined heat transfer rate (Eq. 11):

$$h_{comb} = \frac{Q_{comb}}{A_s(T_b - T_\infty)}$$
$$h_{comb} = 15.7 \text{ W/m}^2\cdot\text{K} \tag{12}$$

After finding the thermal conductivity of the brass rod and calculating the combined (convection + radiation) heat transfer coefficient the students theoretically calculated the temperatures at given locations (Table 1) along the rod by using Equations (1)-(2) and MS Excel® (any spreadsheet program may be useful in plotting the temperature profile along the rod). The detailed instructions of plotting the temperature profile with a spreadsheet computer program can be found in Cakmak (2018a).

In the third step the students did the simulation as described in detail by Cakmak (2018a). The students, then, plotted (Figure 3) the temperature profile distributions (Table 1) found with each method. They saw that although the theoretical and numerical results fitted very well, a slight deviation was observed in experimental results. At this moment they were requested to find a convincing reason for this observation. After plenty of time for discussion among themselves, the students were informed on the concept of measurement uncertainty inevitably found in any experimental measurement and uncertainty propagation in theoretical and numerical calculations which have to be included in the parameters obtained by measurements. Then they calculated the uncertainty propagation in the calculation of combined heat transfer coefficient which was around 6% due to the propagation of primary uncertainties in the temperature and length measurements.

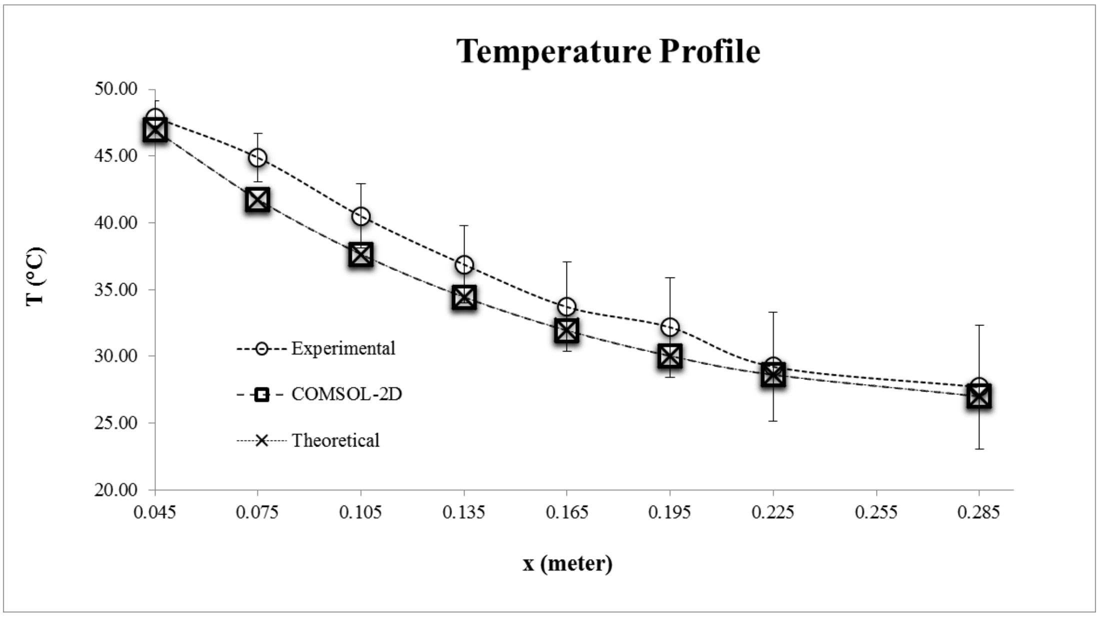

Figure 3:
The results

In addition, the students noticed that the uncertainties found in the measurements incrementally propagated in the temperature calculations done with Equations (1) and (2), as getting close to the tip of the rod (shown by error bars in Figure 3). Then the students acknowledged that the experimental results stayed in the uncertainty ranges of theoretical calculations as well as numerical. Therefore they agreed that the deviations in the experimental results might be omitted and the results of all techniques fitted well to each other.

At the end they were informed that since the results of the numerical simulation strongly depends on the theoretical calculation of the combined heat transfer coefficient, the numerical results should not deviate from the theoretical results, provided that the numerical results are independent of mesh quality and any pre-processing error (e.g. entering wrong thermal conductivity number, using improper boundary condition, forgetting the selection of proper boundary point in 1D).

4. CONCLUSION

The step-by-step instructions for the experimental-theoretical-numerical examination of temperature distribution along a brass rod with constant cross sectional area and insulated tip was thoroughly documented to provide the lecturers willing to teach the concepts of computational simulations and measurement uncertainty in their heat transfer courses via a discovery-based case study. The procedure can easily be extended to include rods with varying tip conditions and different cross-sectional areas. Moreover, it is believed that the method also help students understand other fundamental concepts in heat transfer and differentiate the possible differences in the results obtained by experimental, theoretical, and numerical techniques.

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