The Use of Application Builder & COMSOL Multiphysics as a Tool to Build and Deploy Simulation Apps for Heat Transfer Teaching

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Abstract
For teaching Heat transfer, we currently apply COMSOL Multiphysics software and its new application builder features. Main goals are to maximizing the efficiency of the learning process, expanding the investigation techniques while keeping students engaged. In Engineering based courses as Heat Transfer, simulation apps are helping to strike such a balance by introducing students to complex concepts in a simplified format. In any simulation study, there are complex theories and physics that must be considered in order to obtain accurate, realistic results. Innovative ways that university professors should utilize within the classroom are the use of simulation apps as that they are able to incorporate these elements into the underlying model while hiding such complexities behind a user-friendly interface. Within the university setting, simulation apps are evolving as a powerful tool for introducing students to challenging concepts and enhancing their modeling skills to further advance their learning. We describe the fundamentals and give examples of exercises that include several features of the modelling options. The user-friendly design of COMSOL makes the software well-suited for use in the class-room for both the above-mentioned purposes. The students benefit from the easy handling of model input, which is completely performed within the graphical user interface.

Keywords: Heat transfer and transport, Multiphysics, COMSOL Application builder.

Introduction

1. Heat Transfer Principles

Temperature is considered a common property in physics science and is used to define the hot and cold mediums and boundaries. In microphysics scale principle, the temperature refers to molecular motion intensity [1]. As per Holman's [2], energy movements occur when there is temperature variance between mediums and boundaries. To estimate the energy movements, applying heat transfer science theories and laws is needed. This energy transfer always happens from the hotter medium to the colder one.

Heat transfer has many applications in engineering fields such as chemical engineering, mechanical engineering, civil engineering, biomedical engineering and electronics engineering. The main objectives of heat transfer research are: 1) better energy transfer by increasing heat transfer rate, 2) better insulation by decreasing heat transfer, 3) maintaining the temperature value in specified range.

Heat transfer between mediums has three ways: conduction, convection and radiation. Regards to the study of heat transfer; it is divided into these three parts in this study as:

1.1 Conduction Heat Transfer

Conductive heat transfer is occurring in solid bodies such as metals and walls where heat transfer energy moves from the higher temperature side to the less temperature side. This can be demonstrated in molecular scale, where the higher energy atom due high temperature value collides with the less energy neighboring atom and as a result of this vibrated collision the heat energy will transfer from one side to another [3].

The simple governing equation for steady state conduction heat transfer which is known as Fourier's law of heat conduction is depending on temperature deference, thickness, cross sectional area and material conductivity as follow:

$$q = -kA\frac{dT}{dx} \tag{1}$$

Where:

q is the heat-transfer rate, Watt (W)
A is cross-sectional area, square meter (m^2)
k is the thermal conductivity of the material, W/ (m.K)
dT/dx is the temperature gradient, (k/m)

Transient Heat Conduction

Conservation of energy and the Fourier's law are playing an important role in governing the transient heat conduction, where the heat energy balance can be illustrated in this equation [3]:

[Energy conducted from outside of the medium] + [Heat generated within medium] = [Energy conducted to outside of the medium] + [Change in internal energy within medium]

This heat diffusion equation can be derived in Cartesian format as following.

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c\frac{\partial T}{\partial t} \qquad (2)$$

Where

r is density, kg/m^3

C is the specific heat of material, J/kg. K

$\dot{q}$ is the heat generated per unit volume, W/m^3

1.2 Convection Heat Transfer

Convective heat transfer is the second form of moving the energy from the hot region to the colder region by the movement of a fluid such as liquids and gases [1].

The simple governing equation for convective heat transfer rate is based on the Newton's law of cooling [2]:

$$q = hA\Delta T \qquad (3)$$

Where

q is heat-transfer rate, Watt (W)

h is convection heat transfer coefficient, W/ (m^2. k)

A is area, m^2

ΔT is temperature difference between fluid and surface, K

1.3 Radiation Heat Transfer

The Radiative heat transfer is occurring by the mean of electromagnetic waves where the heat source is sending the heat energy away from the emitting source. The solar energy is considered a clear example for the radiative heat transfer [3].

2. Using COMSOL in heat transfer course

Heat transfer has numerous applications in many engineering fields and with the aid computerized tools, certain packages have been used to investigate, analyze and optimize engineering designs. One of these useful numerical softwares is Comsol Multiphysics which is produced by COMSOL group. This package defined as a finite element analysis, solver and simulation software designed for many Multiphysics fields of science and engineering such as electrical, mechanical, Civil, and chemical applications.

The COMSOL is used in heat transfer course to build and deploy numerical simulation APPS. These APPS are designed as a powerful teaching tool, which will be maximizing the efficiency of the learning process and expand the learning horizons for university students. In addition, COMSOL simulation apps will help students to strike such a balance by introducing them to complex concepts in a simplified visualized format.

To use COMSOL Heat Transfer APPS, a necessary step must be prepared first, which is creating a COMSOL Model to simulate heat transfer domain and process though arranged tasks as following:

a) Domain shape modeling in 1D, 2D, or 3D.
b) Meshing selection from coarse to fine.
c) Subdomain and boundary physical properties settings, where each domain's material property, initial conditions are specified in subdomain settings physics menu, and boundary conditions are specified in boundary settings menu.
d) Selecting the COMSOL Multiphysics's solver. There are two options for this task by either selecting the default setting or choosing the problem designed solver.

The COMSOL app builder in considered a new add-in feature added to the software as an interactive visualized aid in classroom instruction. Once the teacher prepares the problem model, he or she will be able to design an APP for the problem and allow students to manipulate it and try different scenarios. In the next section, examples of some developed APPS for some heat transfer case studies.

3. Sample of Heat Transfer APPS "Case Studies"

Figure (1) displays a snapshot for a COMSOL App. This simple App was created to study the steady state conductive heat transfer where the total heat flux through a brick wall is calculated based on the one dimensional conductive heat transfer governing equation. The App is designed in a simple way to allow students navigate the two section of the problem, where the first section is showing the theoretical background and the second section is divided into multiple numerical analysis tabs (Geometry, Meshing, Temperature profile…etc.). Detailed navigation steps are illustrated in section 5.

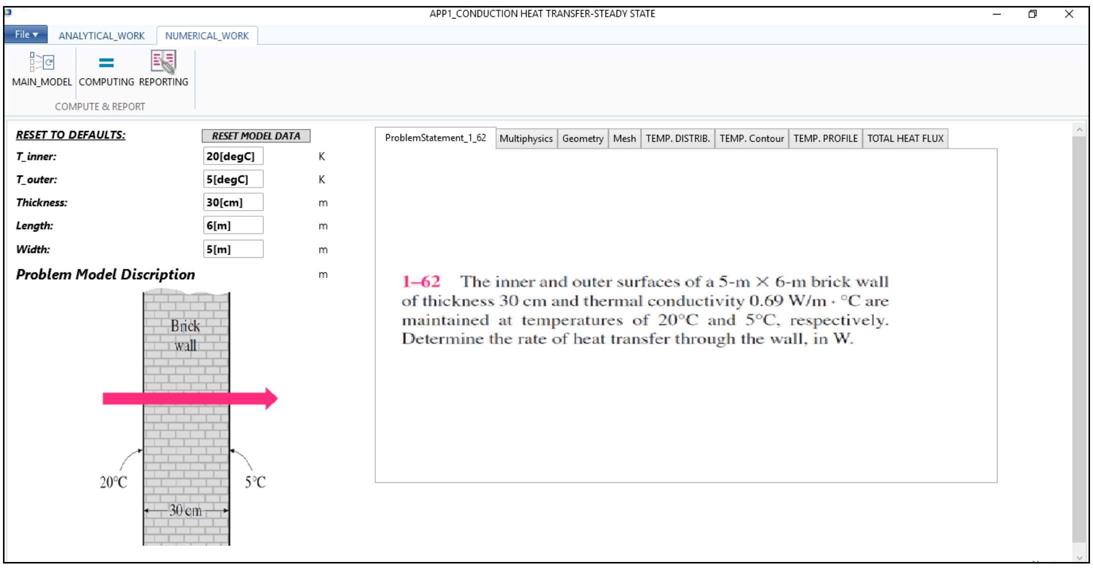

Figure 1: APP-1 snapshot - Solving Conduction Heat Transfer - Steady State case study

APP-2 is presented in figure (2) where a different type of conductive heat transfer is investigated. In this case, change over time “Transient approach” is considered to calculate heat flux loss through a small building roof.

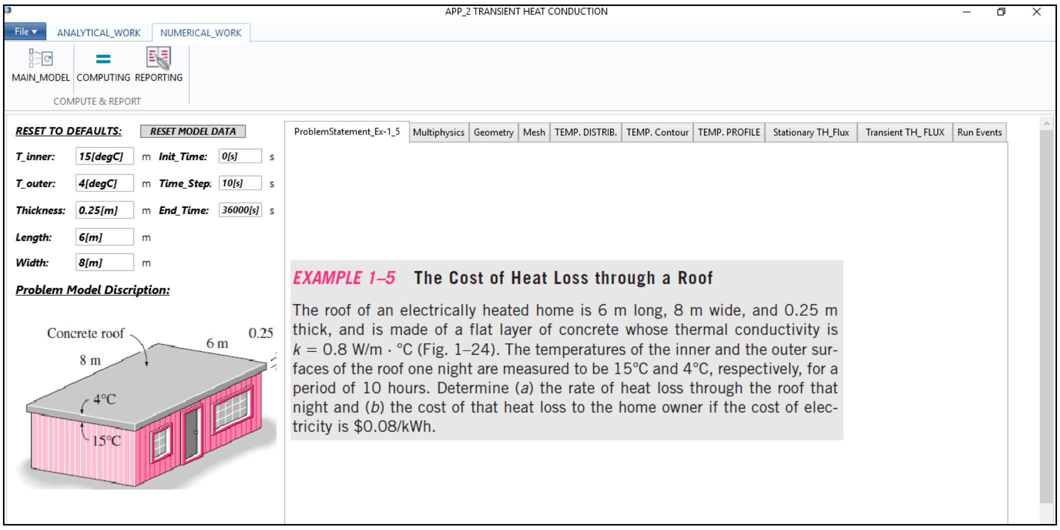

Figure 2: APP-2 snapshot - Solving Conduction Heat Transfer – Transient heat conduction case study

The third sample of using COMSOL Apps in heat transfer course is displayed in figure (3). In this App, two types of heat transfer were covered.

The App is illustrating the combined conductive and convective heat transfer for a case of insulating chamber. The flexibility of the input data section enable student to try different scenarios to find the best way to reach the required insulation needs. In section 6, a detailed investigation for the possible outcome scenarios is presented.

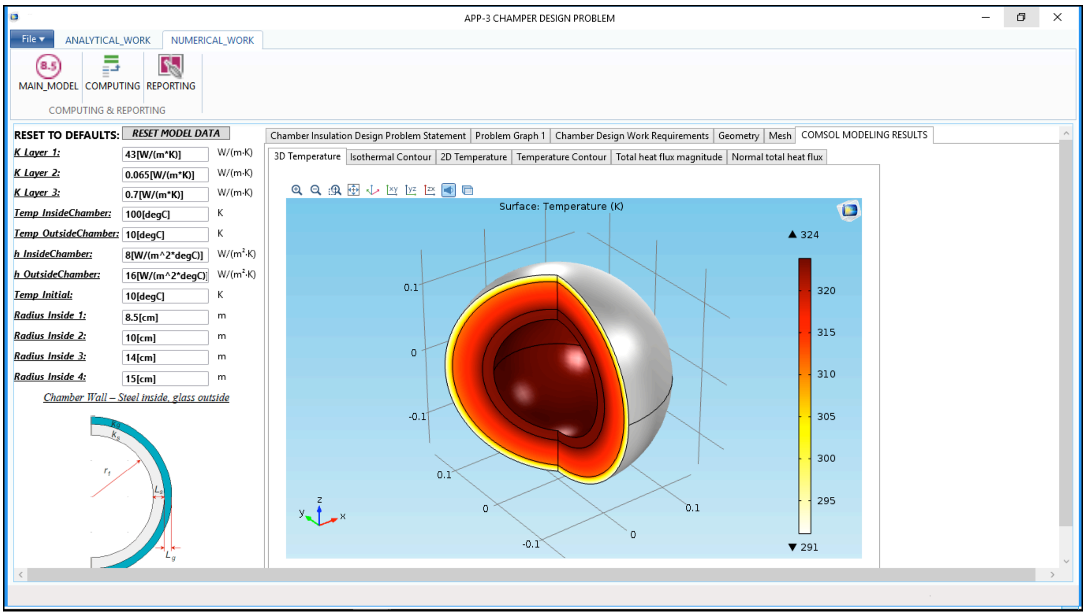

Figure 3: APP-3 snapshot - Solving Conduction/Convection Heat Transfer – Chamber insulation design case study

An oven case study is presented in App 4 as shown in figure (4). The case study is investigating the conductive and convective heat transfer nature.

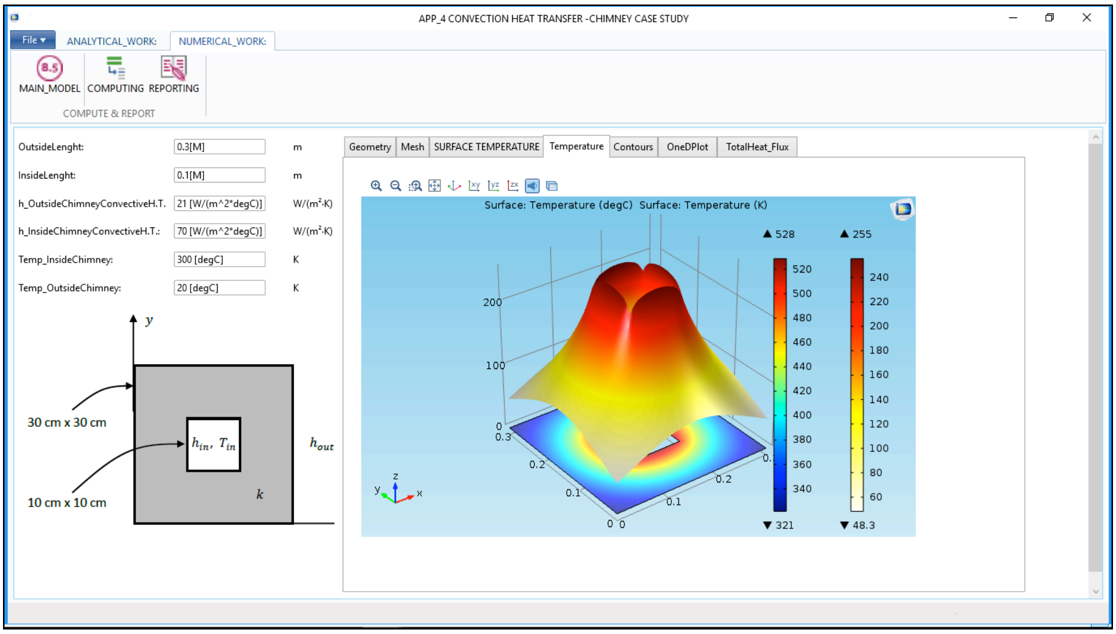

Figure 4: APP-4 snapshot - Solving Conduction/Convection Heat Transfer – Oven heat transfer case study

Another example of using COMSOL Apps in teaching heat transfer is shown in figure (5), where another case of wall insulation is solved based on conductive and convective heat transfer principles.

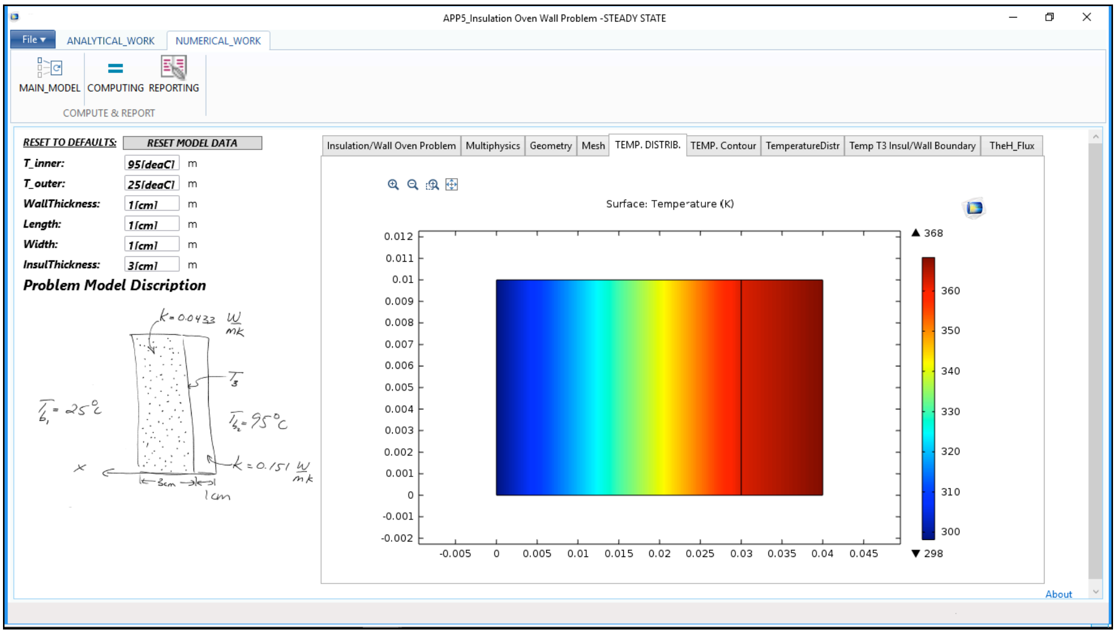

Figure 5: APP-5 snapshot - Solving Conduction/Convection Heat Transfer – Wall insulation case study

One of the main sections in the heat transfer course is studying the radiative heat transfer which has wide range of applications. Figure (6) represents App 6 which was created to study three emissive panels exposed to radiative heat source.

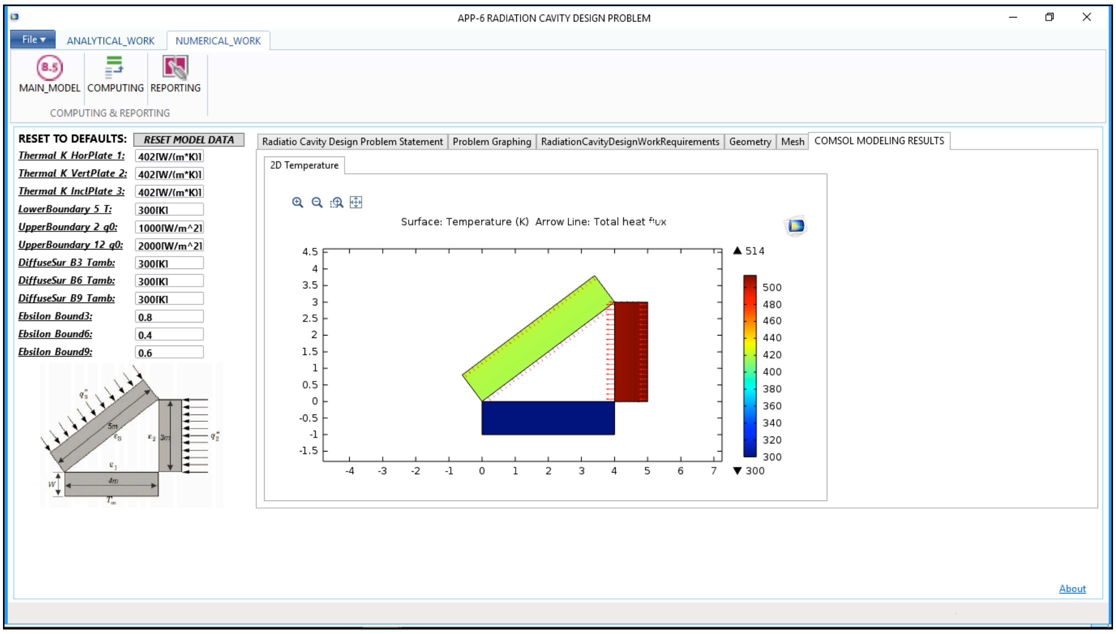

Figure 6: APP-6 snapshot - Solving Radiation Heat Transfer – Three plates case study

4. COMSOL APP Navigation example

To cover all the sides of the simple conductive heat transfer problem, The COMSOL Apps were organized basically into two main dropdown ribbons as presented in the following figures (7) to (19):

- Analytical background works ribbon
- Numerical steps and outcomes ribbon

The analytical work tabs as shown in figure (7) are illustrating the necessary steps that students should preform before starting the numerical work. These steps are sorted as shown in figures (7), (8) and (9).

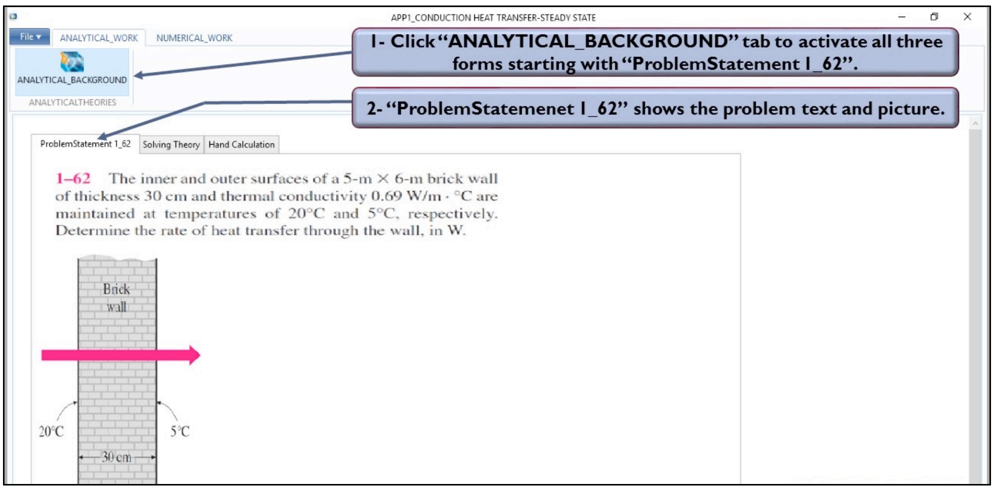

Figure 7: APP-1 navigation snapshot – Analytical background dropdown ribbon components – detailed problem statement tab

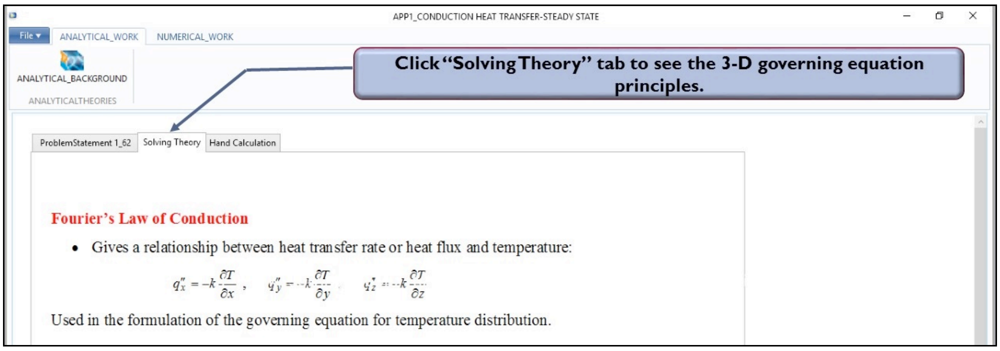

Figure 8: APP-1 navigation snapshot – Analytical background dropdown ribbon components- Solving theory principles

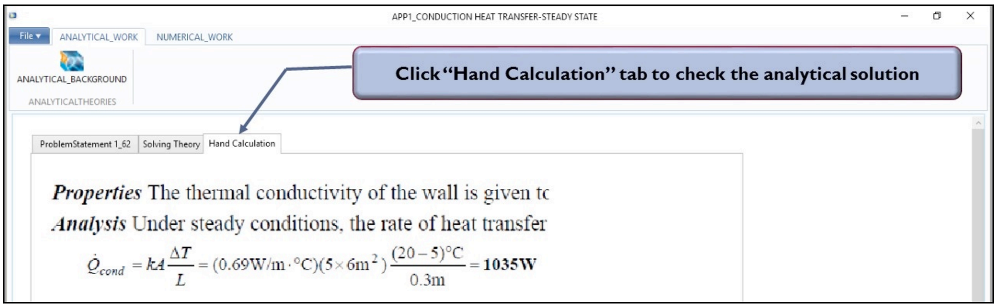

Figure 9: APP-1 navigation snapshot – Analytical background dropdown ribbon components – Formal analytical calculation

Figures (10) to (19) describe the numerical work tabs arrangement. To start the numerical work steps, students should activate all the tabs "forms" associated with the numerical work by clicking the "Main_Model" tab. As shown in figure (10), the first tab on the list for the lift side is showing the repeated problem statement, where students can refer to it easily while staying in the numerical interface. In addition, the figure is displaying the input values section which is designed to be visible all the time while navigating the numerical work tabs.

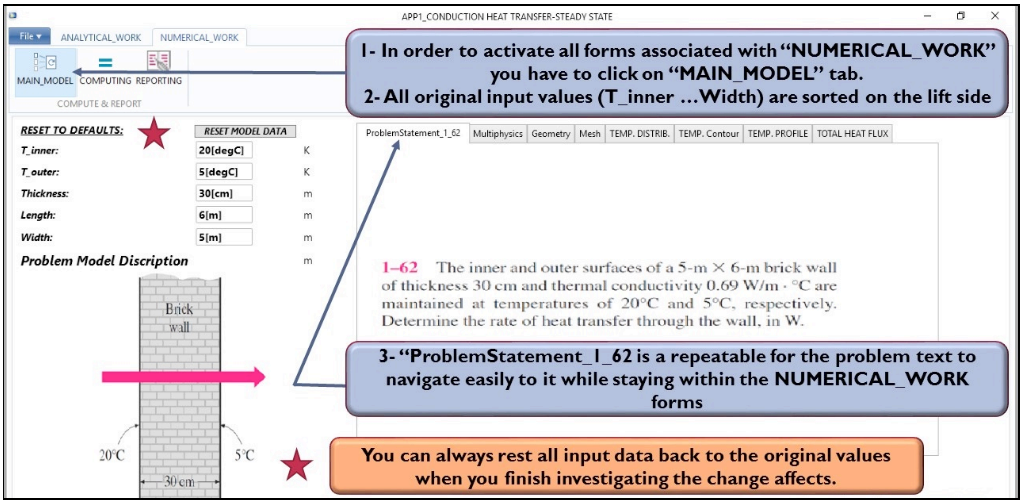

Figure 10: APP-1 navigation snapshot – Numerical work dropdown ribbon components – Activating and inserting problem values

The second tab from the left is displayed in figure (11). This tab is describing the necessary numerical steps such as geometry configuration, meshing visualization... etc.

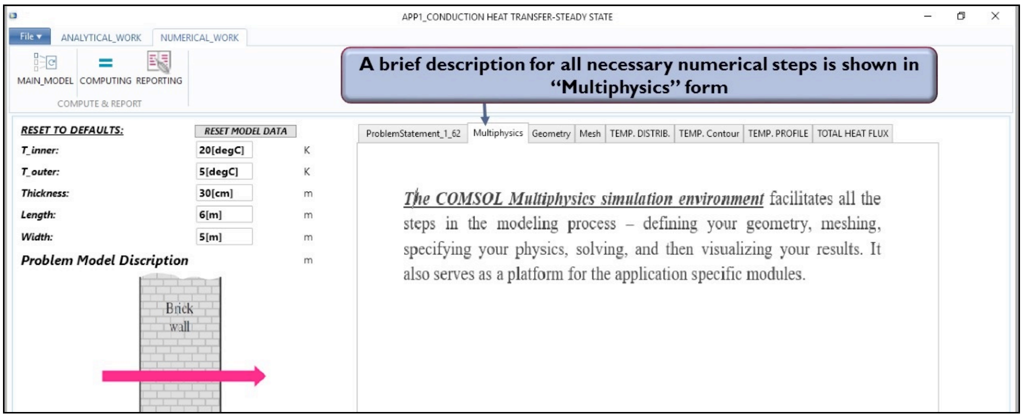

Figure 11: APP-1 navigation snapshot – Numerical work dropdown ribbon components – Multiphysics numerical steps overview

The figure (12) is visualizing the studied geometry in 2-D representation. Noting that both dimensions can be changed from the main control panel.

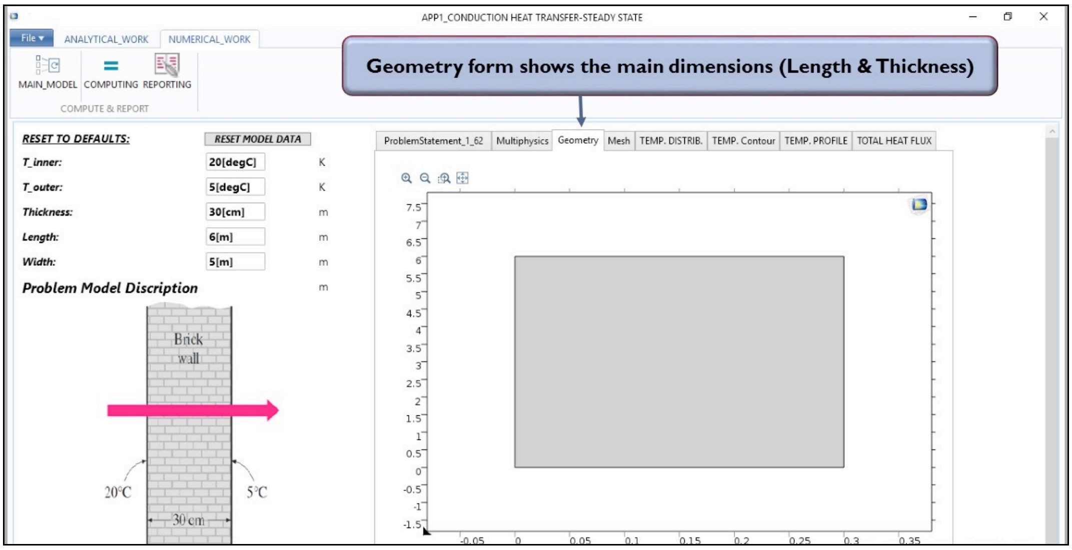

Figure 12: APP-1 navigation snapshot – Numerical work dropdown ribbon components – Geometry configuration and dimensions

Once the geometry is specified in the previous tab, the meshing will be displayed based on the model pre-selection from the coarse meshing grade to the fine meshing grade. The meshing visualization is shown in figure (13)

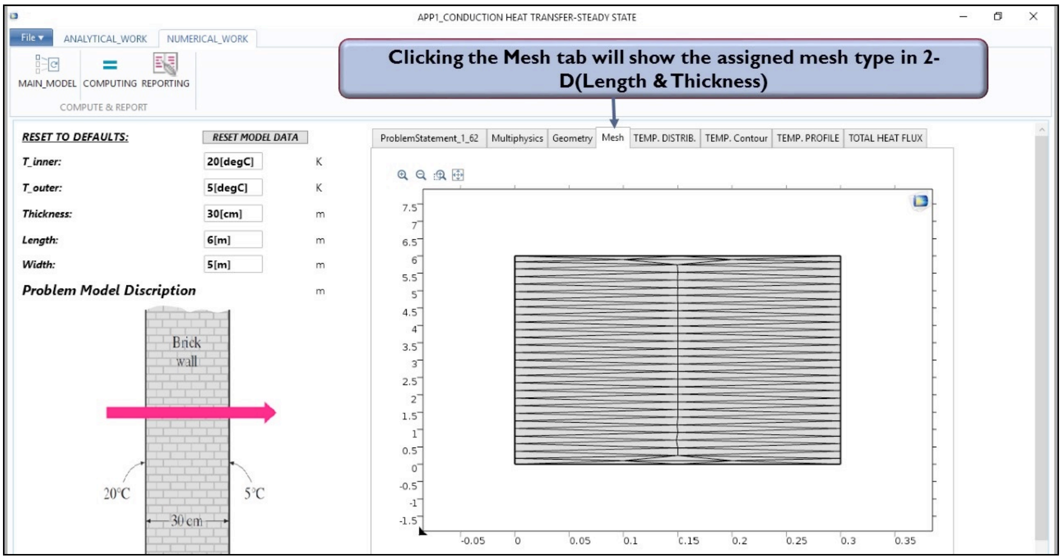

Figure 13: APP-1 navigation snapshot – Numerical work dropdown ribbon components – Meshing visualization tab

The temperature distribution across the geometry is visualized in figure (14) where the gradient color is displaying the temperature values from T-inner value to T-outer value.

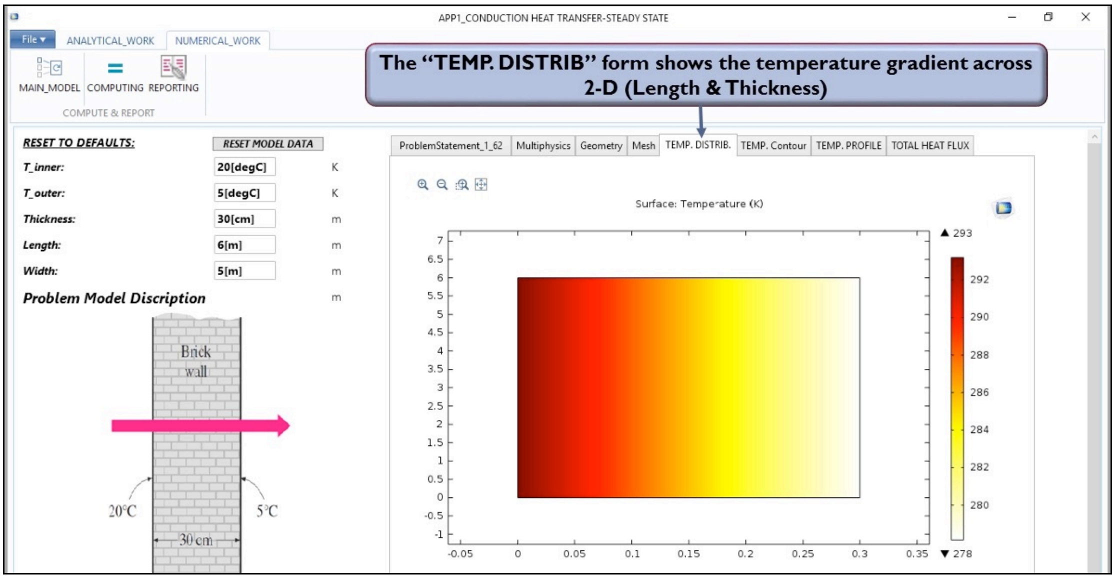

Figure 14: APP-1 navigation snapshot – Numerical work dropdown ribbon components – Temperature distribution across the geometry

Another form of displaying the temperature is shown in figure (15), where the temperature contours is visualized in 2-d (length and thickness).

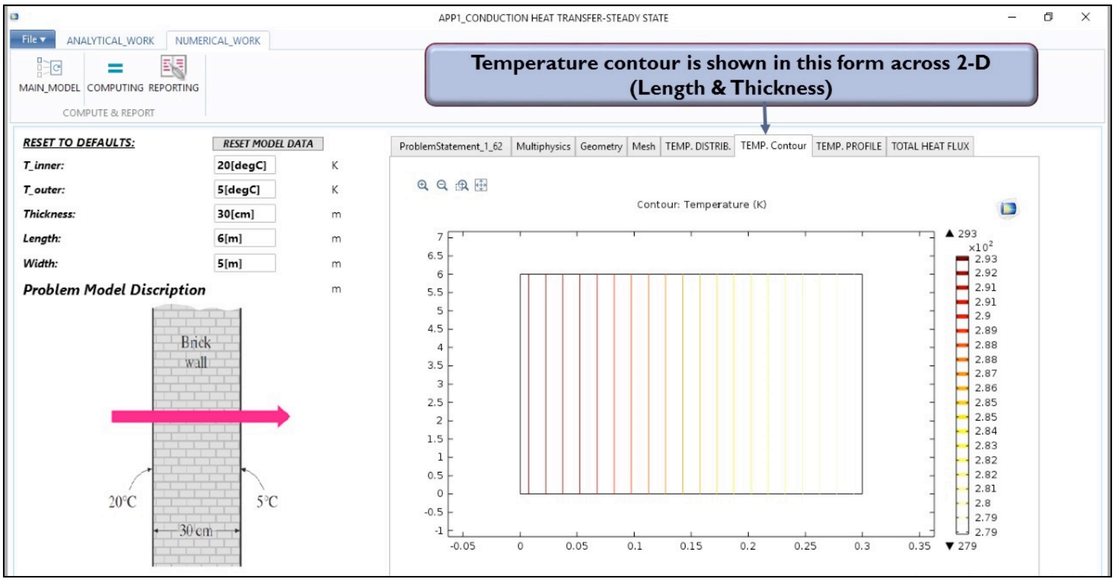

Figure 15: APP-1 navigation snapshot – Numerical work dropdown ribbon components – Temperature contours across the geometry

TEMP. PROFILE tab is displayed in figure (16). This tab is describing the temperature linear function across the wall thickness ranging from the inner temperature in the left side of the graph to the outer temperature in the right side of the graph.

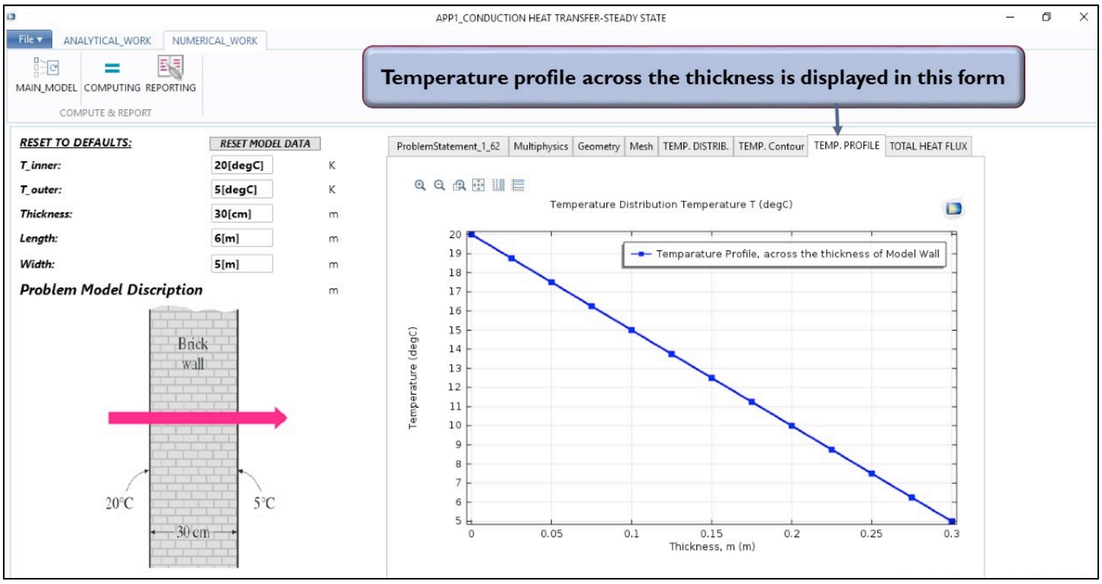

Figure 16: APP-1 navigation snapshot – Numerical work dropdown ribbon components – Temperature profile across the wall thickness

The last tab at the right end in figure (17) is showing the numerical value for the total heat flux loss across the wall thickness. From this tab students, can compare their analytical results with this value and their finding should be within the acceptable value based on the numerical approximation and meshing scale.

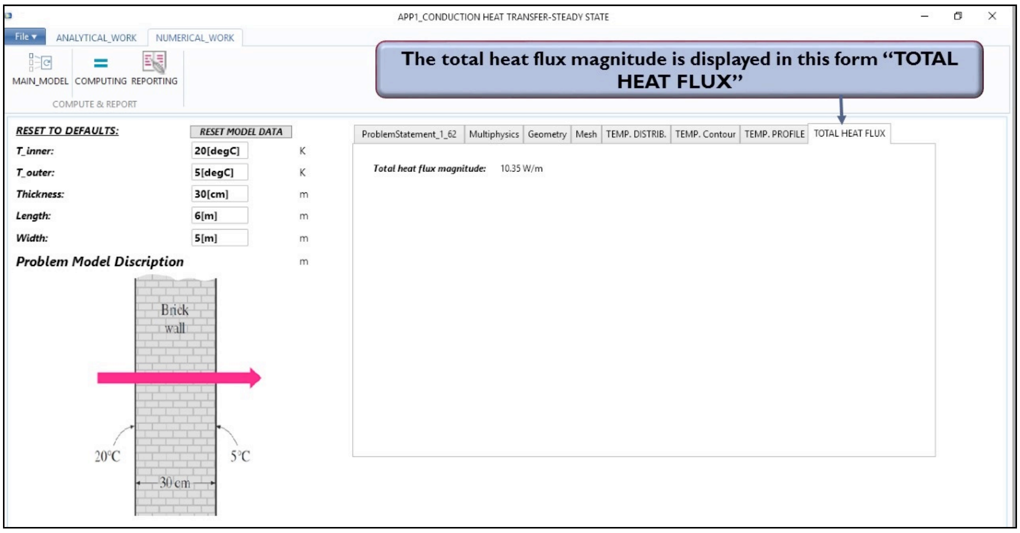

Figure 17: APP-1 navigation snapshot – Numerical work dropdown ribbon components – Total heat flux loss across the wall

Once students apply any changes to the input values they should perform the computing process by clicking the "COMPUTING" tab as described in figure (18). This step will run all the numerical models and give the finish signal "sound tone".

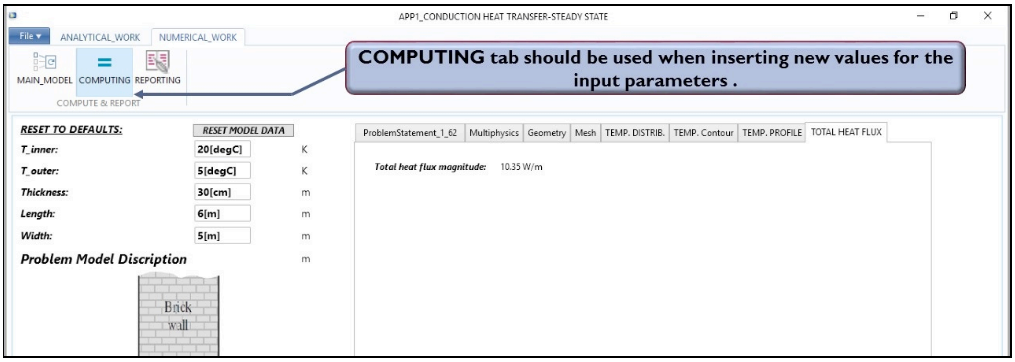

Figure 18: APP-1 navigation snapshot – Numerical work dropdown ribbon components – Numerical computing step

The APP is equipped with a very useful reporting feature as shown in figure (19). By this step, students can extract an editable Microsoft Word file which has pre-arranged report section as displayed in figure (20). The file can be saved later in the desired directory. The produced technical report will have the main sections such as cover page, table of contents, input list, charts and colored plots.

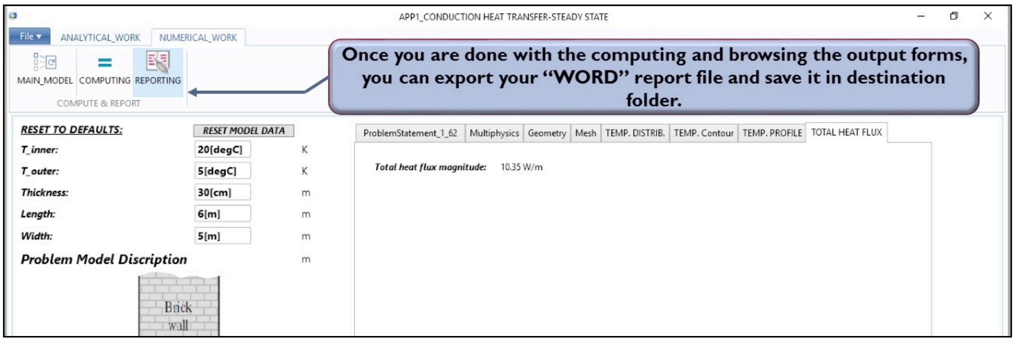

Figure 19: APP-1 navigation snapshot – Numerical work dropdown ribbon components – Extracting the final study report

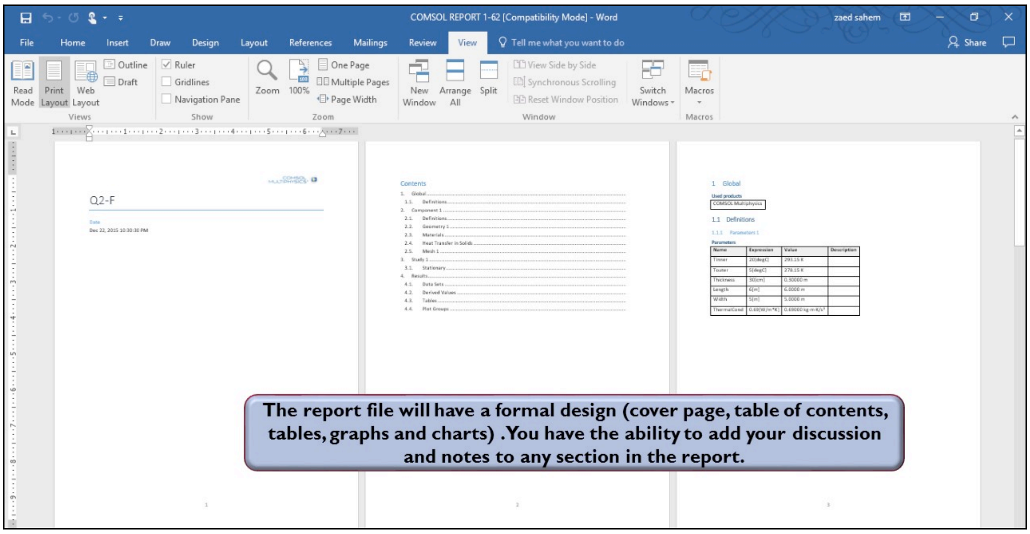

Figure 20: APP-1 editable produced report

5. Results Overview for APP-3 "Chamber insulation design case study - Comparison of case study six possible scenarios"

By implementing any change to the input values, students will be able to see the results of that change. In this section, App-3 is dealing with a case study of finding the best way of insulating a chamber. Therefore, the possible arrangements for the chamber layers are described in the following table as displayed in figure (21). Students can make the adjustments to the layer diameters with some pre-set restrictions

- The inner and outer diameters for the whole set is constant
- The thickness of each layer is kept at constant values
- The inner and outer temperatures are kept at constant values
- The inner and outer convective heat transfer coefficients are constant

Scenario	Inner layer	Mid layer	Outer layer
S1	Steel	Insulation	Glass
S2	Insulation	Steel	Glass
S3	Glass	Insulation	Steel
S4	Glass	Steel	Insulation
S5	Steel	Glass	Insulation
S6	Insulation	Glass	Steel

Figure 21: APP-3 possible problem scenarios (layers arrangement)

The first scenario was arranged as the steel will be in the inner layer and the insulation material in the mid layer and the glass for the outer layer as shown in figure (22)

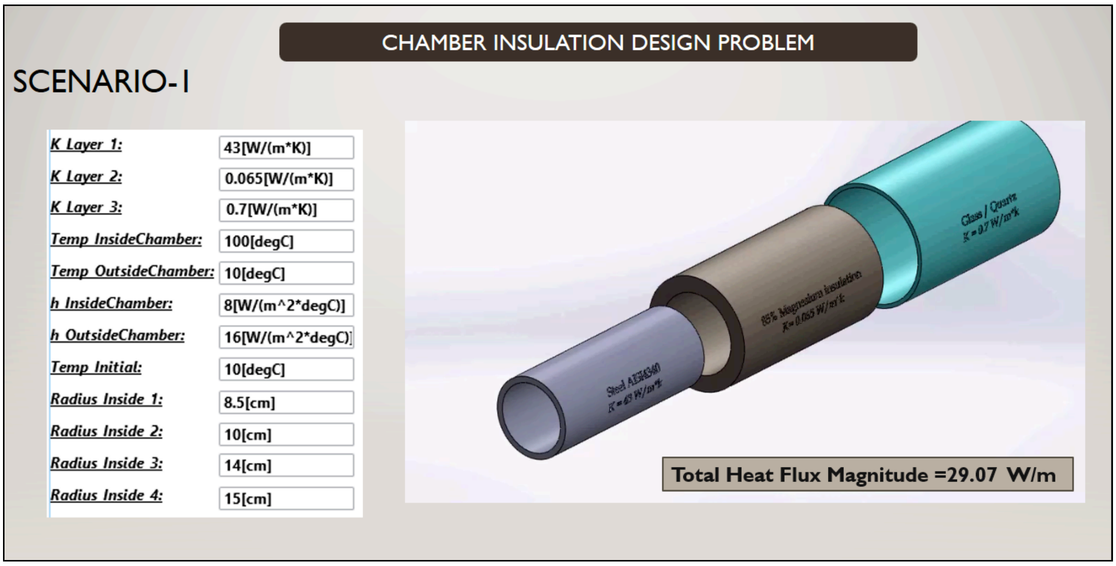

Figure 22: APP-3 First scenario (inner-layer: steel, mid-layer: insulation, outer layer: glass)

Figure (23) is illustrating the second scenario configuration, where the insulation material is positioned in the inner layer and the steel in the mid layer and the glass for the outer layer.

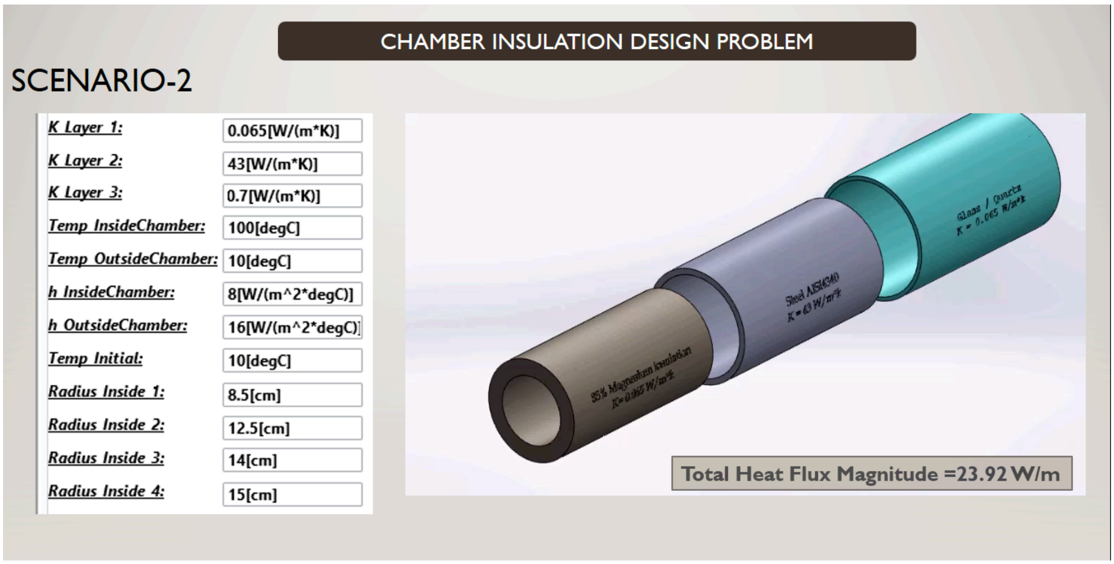

Figure 23: APP-3 Second scenario (inner-layer: steel, mid-layer: insulation, outer layer: glass)

The third possible scenario as shown in figure (24) is organized as the glass is placed in the inner layer and the insulation material in the mid layer and the steel for the outer layer.

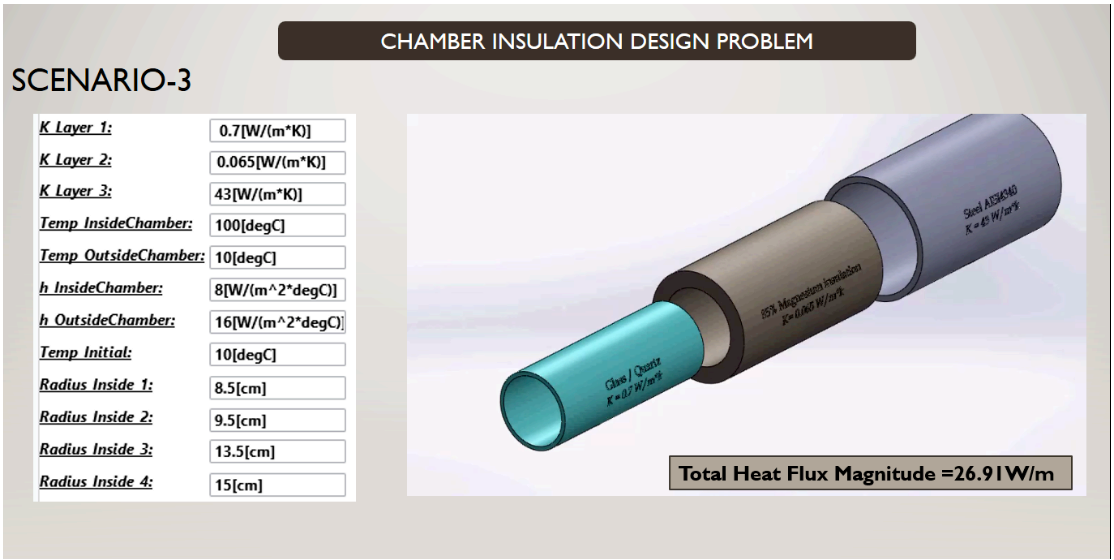

Figure 24: APP-3 Third scenario (inner-layer: steel, mid-layer: insulation, outer layer: glass)

The arrangement for the whole set in fourth scenario as shown in figure (25) is selected to be the glass layer in the inner position and the steel in mid layer and the insulation material is covering the set as outer layer.

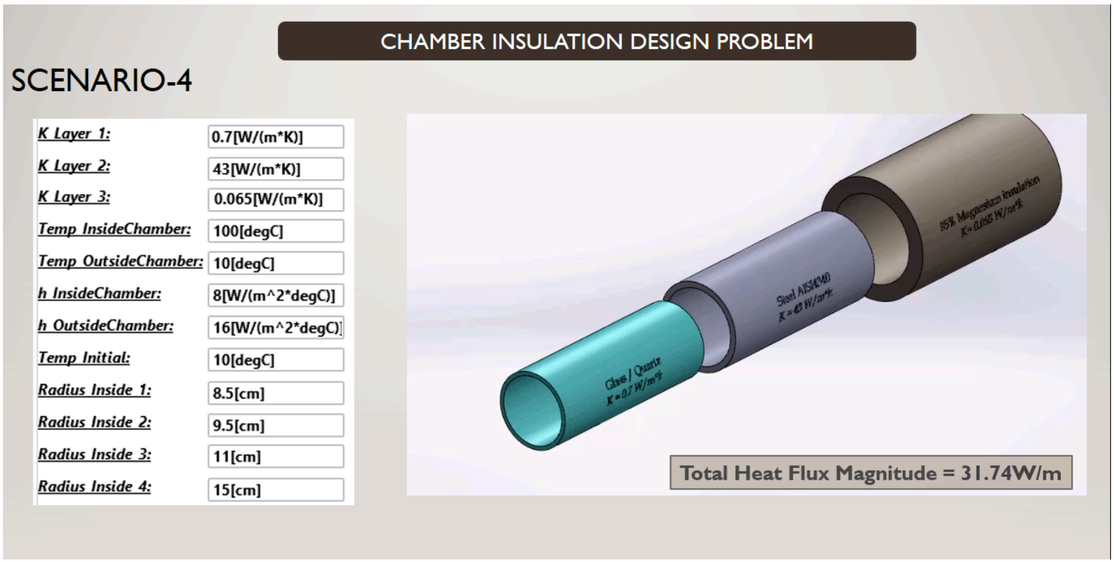

Figure 25: APP-3 Fourth scenario (inner-layer: steel, mid-layer: insulation, outer layer: glass)

The fifth scenario was sorted as the steel will be in the inner layer and the glass in the mid layer and the insulation for the outer layer as displayed in figure (26)

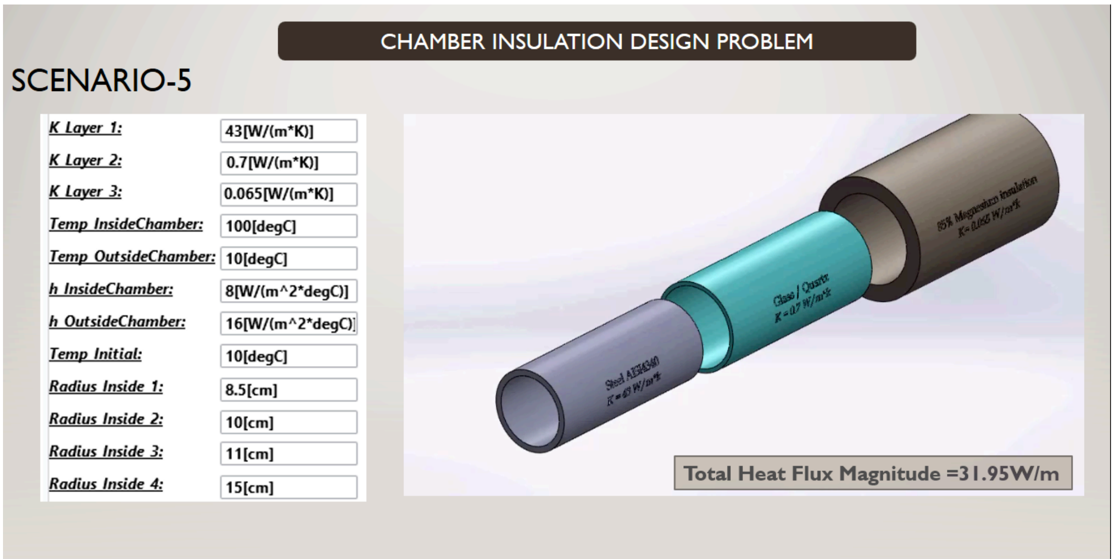

Figure 26: APP-3 Fifth scenario (inner-layer: steel, mid-layer: insulation, outer layer: glass)

The sixth possible scenario as shown in figure (27) is arranged as the insulation material is positioned in the inner layer and the glass in the mid layer and the steel is covering the set as an outer layer.

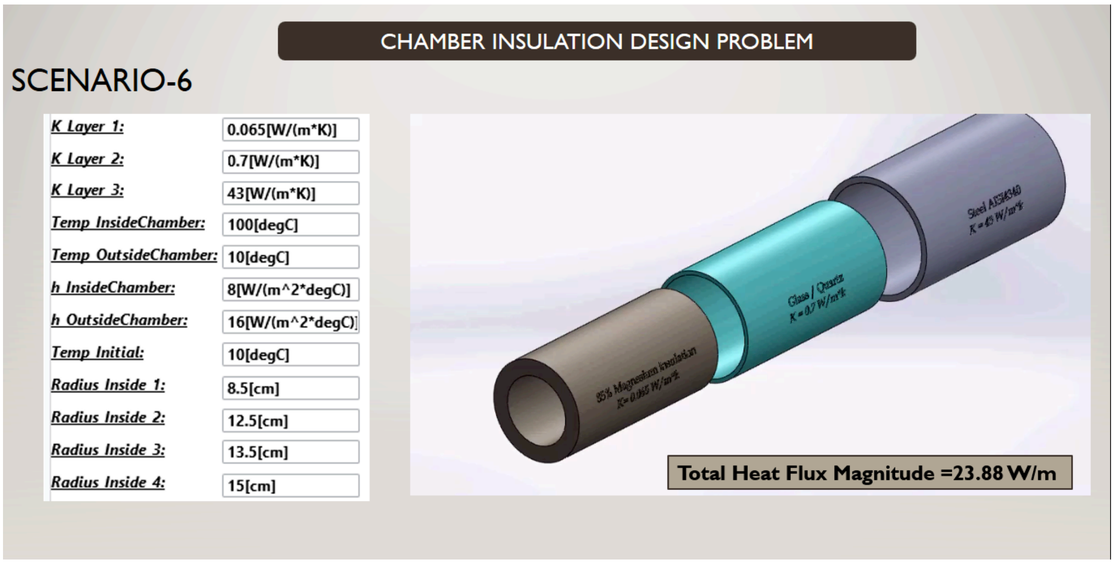

Figure 27: APP-3 Sixth scenario (inner-layer: steel, mid-layer: insulation, outer layer: glass)

By exporting the results of these scenarios to another data analysis software such as MS excel students can compare the resulted values for the total heat flux loss across the layers set and determine the optimum design selection based on the pre-set assumptions. Figure (28) shows MS excel comparison chart for the six possible scenarios as described in figure (21).

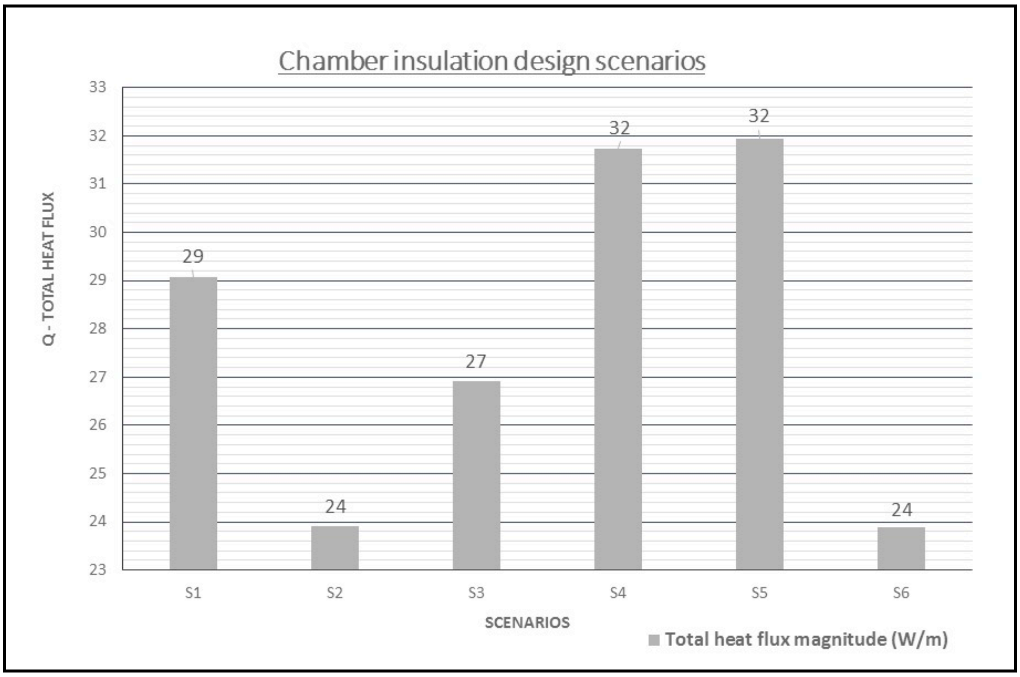

Figure 28: APP-3 Scenarios comparison chart

Conclusion

The aim of this scientific work is to deepen and consolidate the students' knowledge in the fields of heat transfer which is considered one of the important courses at the undergraduate studies level. Using simulation techniques and tools as an advanced teaching aid was an introduction to building the course APPS. These APPS were created by COMSOL Multiphysics by using the built-in APP builder feature.

Comsol Multiphysics deployed APPS are very useful instrument to reach this goal. Even the problems linked to finite element calculations help students to understand processes as well as solution methods. It has been noted that expanding knowledge is gained through different problem boundary conditions. This work reveals that visualized results in the APPS are changeable once the student control the input data and because of their changes they can produce variety of scenarios based on their physics assumptions. However, the future versions of these APPS can be improved by designing POP_UP and hover navigations windows for students to self-guide them while working on these APPS.

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