Improving the quality of engineering education: using a Pitot tube system at fluid mechanics laboratories

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Abstract
In the present work, academic results concerning modifications in fluid mechanical laboratories and measurements with a simple Pitot tube at a Brazilian university are presented. Considering the current objectives of engineering teaching, the Physics Education Research Group (GruPEFE) has been developing didactic materials and technologies at fluid mechanics laboratories, which are used by approximately ten thousand students in several engineering fields, per semester. The group has a research field dedicated to develop cheaper and faster technologies for practical class optimization, which leads to a higher-level learning, as it creates an analyzing environment and promote an active learning at the laboratories. In this context, results concerning a simple Pitot experiment are presented with some important issues that can be addressed in practical classes as the relationship between velocity and flow rate and the water velocity profile in a fully developed pipe flow. A good agreement (± 2%) between the theoretical and the experimental fluid velocity profile was found.

Keywords
Fluid mechanics, engineering education, Pitot tube, water velocity profile.

1. Introduction
During the last years, universities rationalized their engineering curricula, associated with cost cuts that have led to a reduction of credit hours, as point out by Russel et al. (2000). According to Agrawal and Khan (2008) education quality is a matter of concern for all its stakeholders, which requires educators and educational administrators to demonstrate that educational institutions are capable of providing high-quality educational opportunities at a reasonable cost.

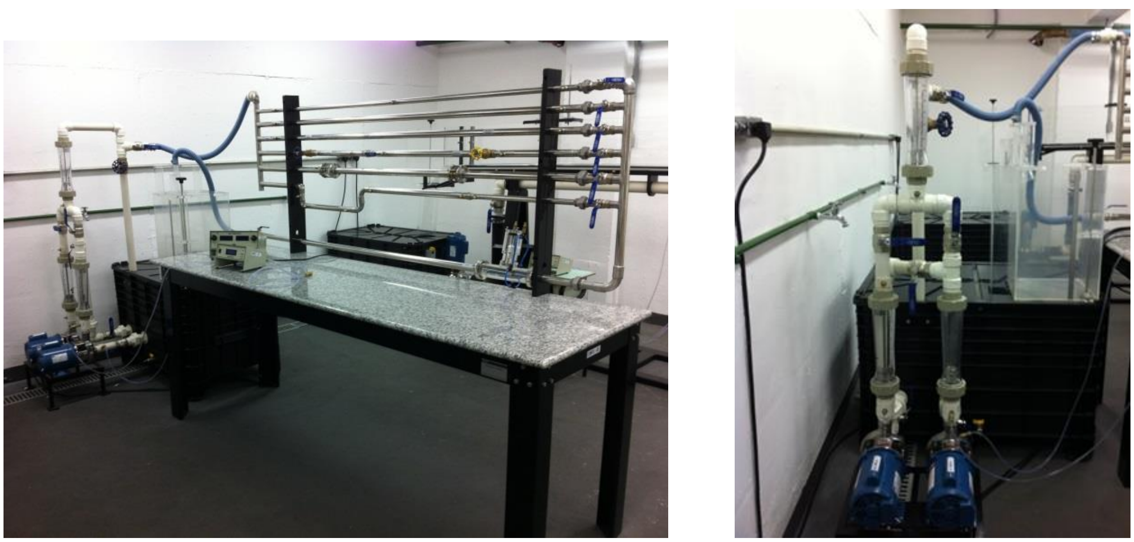
In this context, the Physics Education Research Group (GruPEFE) was created at engineering undergraduate course at Universidade Paulista (UNIP), located in Brazil, which teaches engineering since 1977. In order to get results in agreement to the engineer professional life, the group has a research field dedicated to develop cheaper and faster technologies for practical class optimization. Considering the current objectives of engineering teaching, the GruPEFE is developing didactic materials (Ferreira and Cavalheri (2014) and Santos and Ferreira (2015)) and technologies at fluid mechanics laboratories, which are used by approximately ten thousand students in several engineering fields (Civil, Mechanical, Automation, Production, Aeronautical and Petroleum), per semester.

The teacher and student experiences in classroom are considered to develop new didactic equipment and methodologies, as a new Pitot tube system, which will be described in the present work. Pitot tube systems are widely used by industry and research. In literature, Replogle and Wahlin (2000) present a simple Pitot tube system developed with cheaper materials and that can be used to measure the fluid velocity at several points across the piper diameter (in a system to lift water in canals). Lynn et al (2014) describe an S-type Pitot tube system to determine fluid velocity at low flows (< 2.4 m³/h) and pressure difference (< 100 Pa).

Based on the above, the GruPEFE has performed some improvements on fluid mechanics laboratories and developed an economical, practical and robust Pitot tube system able to measure low-pressure difference (≈ 50 Pa) in a 32 mm cross section of a pipe, analyzing different flow values (from 7.25 to 8.5 m³/h). This system provides experimental results consistent with fluid mechanicals theory. The main purpose of the system improvements summarized above was to optimize practical classes and lead to higher-level learning, as it creates an analyzing environment, promote an active learning at the laboratories and enhance the student interest on the physical phenomena associated (Matthews (2000)). This new approach is based on the education philosophy of constructivism formulated by John Dewey (1938) and on the education philosophy of critical pedagogy, which was influenced and widespread in Brazil by Paulo Freire (2000). From these perspectives the main focus should be on activities inside classroom, on which instruction must create an active role for the learner and the learner must construct his own knowledge by the means of a critical reflection of the concepts presented in class.

2. Materials and Methods

The setup developed for practical classes of fluid mechanics consists of a stainless steel pipeline (see Figure 1-a) with different branches, allowing multi parametrical measurements. Previously, all the pipes were made of PVC. Although, PVC is a cheap material its durability and maintenance are not suitable, considering the extensive usage of the fluids workbench at the fluids laboratories in UNIP. Moreover, PVC is strongly influenced by temperature variation which caused leak problems during the practical classes.



(a) (b)

Figure 1: (a) System used for fluid mechanics practical classes and (b) rotameters connected to the water pumps.

The fluid analyzed is water and this system allows studying different fluid meters (Pitot tube, Venturi and orifice meter), valve flow characteristics, singular and distributed head losses and pump association (series or parallel) (Figure 2). Furthermore, the system has rotameters (0.5 m³/h resolution) connected to the pumps, which enables measuring the flow rate of water (Figure 1-b). In one of the pipe branches, there is an acrylic tube (40 mm diameter) inserted with a simple Pitot tube, made of stainless steel, in which the distance can be varied across the acrylic tube by the means of a linear scale (1.0 mm resolution). Details of this assembly are depicted in Figure 3.

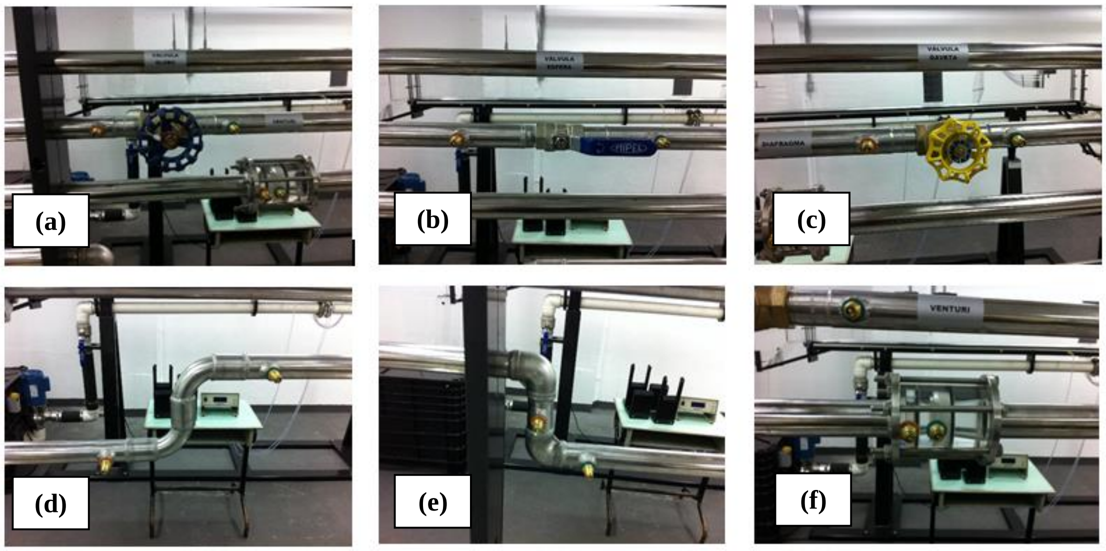
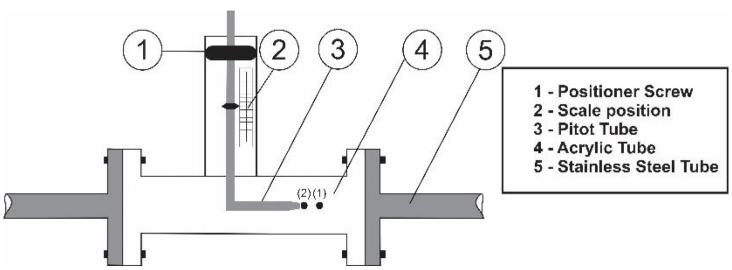
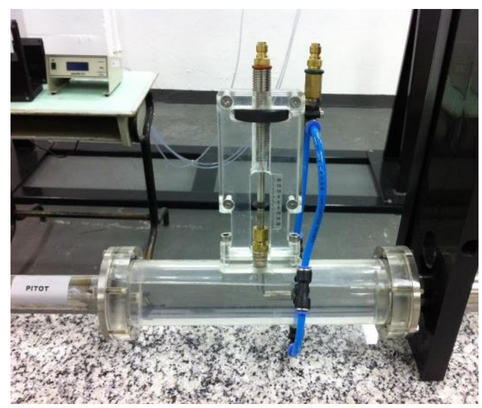


Figure 2: View of the system, showing the valves and pipes used to study singular head losses: (a) Globe (b) ball and (c) gate valve; (d) curved and (e) elbow pipe. Flow meter connected to the system: (f) Venturi tube.



(a)



(b)

Figure 3: (a) Schematic drawing of Pitot tube with linear scale to study the fluid velocity profile across the tube diameter (b) View of the Pitot tube in the system.

Previously, u-tube manometers filled with mercury were used at the fluid mechanics laboratories for pressure drop measurements across the Pitot tube. With the u-tube manometers the students had to relate the differential pressure ΔP with the observing difference h between the levels of mercury in the two halves of the u-tube, using the differential manometer equation $\Delta P = (\gamma_{Hg} - \gamma_{water}).h$, where γ_{Hg} is the specific weight of mercury and γ_{water} is the specific weight of water. Therefore, to perform differential pressure measurements with u-tube manometer near to the wall of the pipes, which is the objective of the Pitot experiment, was a difficult task since it resulted in values of the same magnitude as the instrumental resolution. Then, in order to increase the system sensitivity to low differential pressure, the mercury was replaced by bromoform as manometer fluid, but since bromoform is toxic, to reduce the occupational exposure to this fluid and provide the required sensitivity, minimizing the data acquisition time, digital manometers were specially developed for that purpose (see Figure 4).

Figure 4: Digital manometer specially developed for fluid mechanics practical classes.

From fluid mechanics theory (Fox and McDonald's (2011) and Brunetti (2008)), the fluid velocity v_1 can be determined considering the Bernoulli equation at point (1) and (2) on a streamline (Figure 2-a):

$$z_1 + \frac{p_1}{\gamma_{water}} + \frac{1}{2g} \cdot v_1^2 = z_2 + \frac{p_2}{\gamma_{water}} + \frac{1}{2g} \cdot v_2^2 \qquad (1)$$

where:
v_1 and v_2 are the fluid flow velocity at points (1) and (2) on a streamline;
g is the value of acceleration due to gravity;
z_1 and z_2 are the elevation of the points above a reference plane;
p_1 and p_2 are the pressure at the chosen points, and
γ_{water} is the specific weight of the water at all points in the fluid and the value considered in the following analyses was 10000 N/m³.

Thus, as the velocity at the stagnation point of Pitot tube is zero, the fluid velocity v_1 can be calculated by the following relation:

$$v_1 = \sqrt{\frac{2 \cdot g \cdot (p_2 - p_1)}{\gamma_{water}}} \qquad (2)$$

Therefore, by connecting a manometer to the Pitot tube and at the pipe wall is possible to measure the pressure drop across points (1) and (2), and so determine de fluid velocity. In the present work, results concerning a simple Pitot experiment are presented with some important issues that can be addressed in practical classes as the relationship of velocity and the flow rate (ranging from 7.25 to 8.5 m³/h) and the agreement between the theoretical and the experimental water velocity profile in a fully developed pipe flow, considering that the velocity profile v can be written in terms of the maximum velocity (v_{max}) as:

$$v = v_{max} \left[1 - \left(\frac{r}{R} \right)^2 \right] \qquad (3)$$

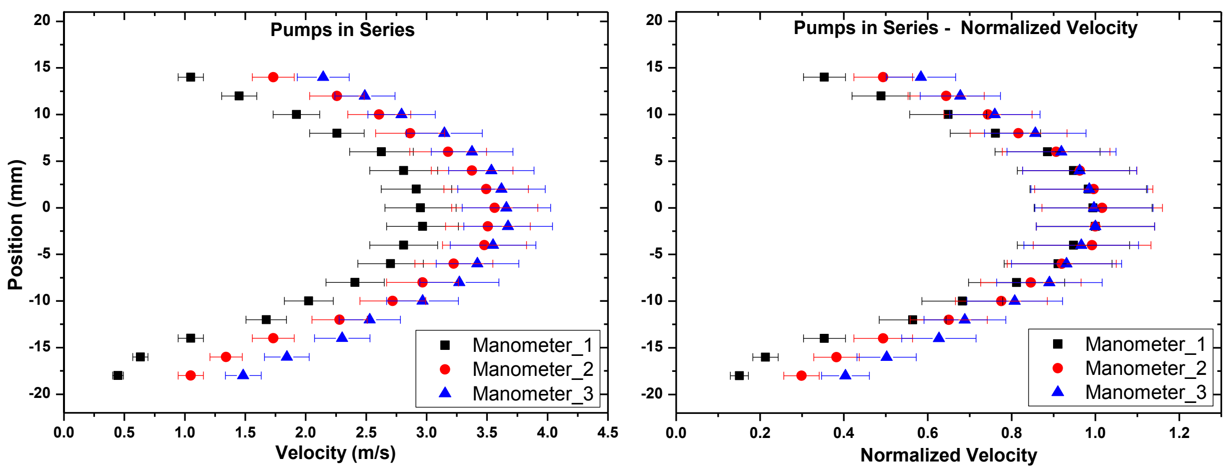
where r is the position from the pipe center and R is the pipe radius.

Furthermore, the standard system has two pumps with similar performances (550 W), so the influence of the pump association (in series or parallel) can be analyzed.

3. Results and Discussion

In order to test the reliability of the instruments and to validate the didactic technique, measurements of differential pressure across 32 mm of the pipe, with three different manometers and a volumetric flow rate equal to 8.7 m³/h were performed using two pumps in series. By means of Equation (2), the water velocity was determined and the results are shown in Figure 5-a. It is worth noting that the error bars represented consist with instrumental uncertainties and correspond to ± 10% of the velocity value. The discrepancies of data sets are due to the calibration of the manometers, but since the main objective of this practical class is to study the Pitot tube operating principle and not to perform absolute precise measurements, these variations are irrelevant.

In Figure 5-b the velocity data determined from the differential pressure, measured by the three manometers were normalized to the maximum value. Therefore, is possible to verify the consistency of the result trends from the different manometers developed for the fluid laboratories. Considering this simple experiment and analysis is possible to discuss concepts taught in classroom in former semesters of the engineering courses as differential pressure measurements and meters, the Pitot tube principle of operation and fully developed flow among infinite parallel plates. According to the basic fluid mechanics theory (Fox and McDonald's (2011) and Brunetti (2008)), this parabolic profile is due to the fact that close to the pipe walls the friction causes a decrease in fluid velocity. On the other hand, for incompressible flow, mass conservation requires that the velocity in the central frictionless region of the pipe must increase to compensate.



(a) (b)

Figure 5: (a) Water velocity profile in a 40 mm diameter pipe measured with a Pitot tube with three different manometers developed for practical classes with volumetric flow rate equal to 8.7 m³/h and (b) Normalized velocity across the pipe considering the differential pressure measured by the three manometers analyzed.

The agreement between water velocity values across the pipe obtained in three independent data sets named Data1, 2 and 3, measured with the manometer_2 and with two water pumps in series are shown in Figure 6 and evidence the repeatability of the results and the system stability.

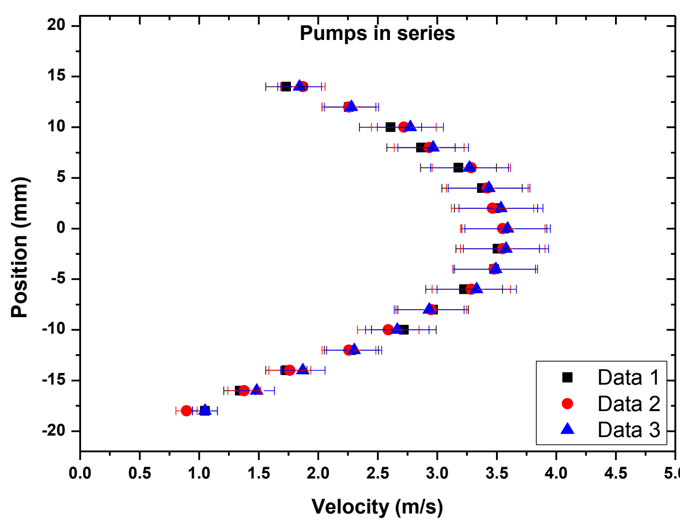


Figure 6: Data sets referring to independent measurements performed with manometer_2 and two water pumps in series.

The parabolic shape of the velocity profile was analyzed by means of fitting the function shown in Equation (3) to "Data 2" (Figure 7). It is worth noting that, for didactic purposes the water velocity is analyzed in the horizontal axis and the radial position in a pipe in the vertical axis, but in Figure 5 the position, which is the independent variable, is kept in the horizontal axis. The agreement (± 2%) between the experimental data and the theoretical curve is evident in Figure 5.

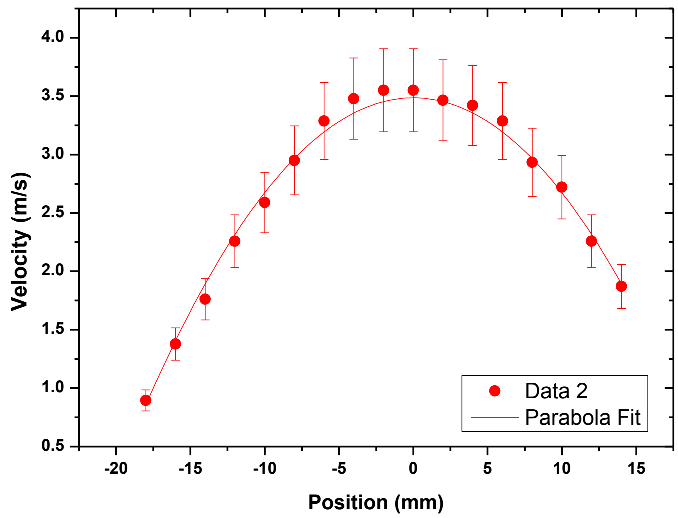


Figure 7: Parabolic fit of experimental Data 2, considering the theoretical velocity profile in a fully developed pipe flow.

As previously mentioned, with the present system the influence of the water pump association can be studied. When the pumps are in series their flow rates are identical and the heads produced are added. Whereas when pumps are in parallel the generated head is the same for the pumps and the total flow rate is the sum of the flow rates of each pump. Thus, in order to study this influence, measurements of the velocity profile across the pipe were performed with both associations and are presented in Figure 8. In this analysis, both measurements agree within their quoted uncertainties.

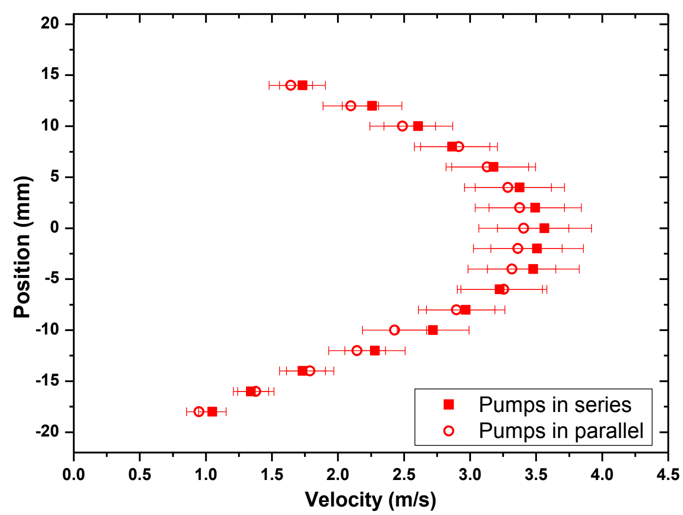


Figure 8: Water velocity across a pipe, measured with a Pitot tube and using two pumps in series and two pumps in parallel.

In order to study the qualitatively relation between the fluid velocity and the flow rate, measurements of the maximum velocity (at the central axis of the pipe) were performed with the Pitot tube, connecting the two pumps in series and in parallel (see Figure 9). As expected, no significant difference was observed.

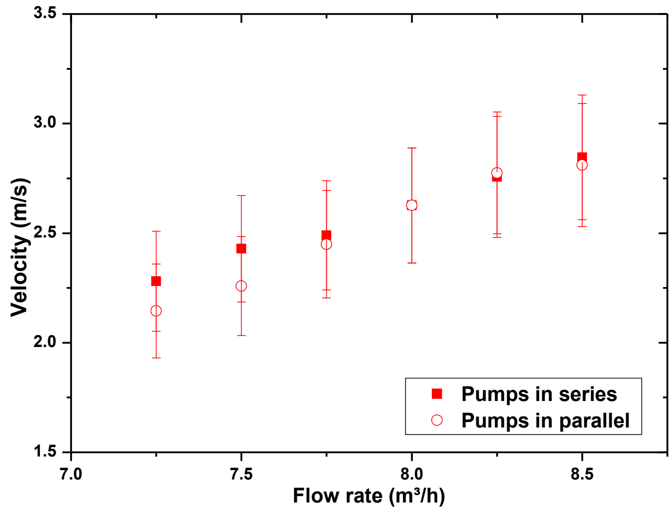


Figure 9: Fluid velocity versus flow rate data with pumps connected in series and in parallel.

Conclusions

Based on the current objectives of the engineering teaching, the GruPEFE is developing didactic materials and technologies at fluid mechanics laboratories. In this context, our group has developed an economical, practical and robust Pitot tube system able to measure low-pressure difference across a pipe and analyze different fluid flow rates. This system provides experimental results concerning water velocity profile in good agreement with fluid mechanicals theory, which is demonstrated by the use of the parabolic fit of a fully developed flow.

The improvements performed in systems optimized practical class and create an analyzing environment, promoting an active learning at the laboratories and enhancing the student interest on the physical phenomena associated. Furthermore, since Pitot tubes are widely used by industry and research area, this measuring system provides results in agreement to the engineer professional life.

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Biography

Pedro José Gabriel Ferreira is currently coordinator of Engineering Course, professor, coordinator of laboratories and member of GruPEFFE at Universidade Paulista – UNIP. Mr Ferreira holds Bachelor a degree in Control and Automation Engineering from Universidade Paulista – UNIP, concluded in 2004. After graduating, he studied from 2006 to 2007 a post-graduation course (latu sensu) in Teacher Training for Higher Education at UNIP. In 2009 he enrolled in a post-graduation Masters in Production Engineering from UNIP and concluded it in 2011. From 2004 to 2009 worked as an Engineer at Ultragaz Company in the liquefied petroleum gas market. The main activities developed were in the areas of Production, Maintenance, Engineering Projects, Industrial Painting Process, Inspection of pressure vessels and technical tests.

Iara Batista de Lima is currently professor of Engineering Course (Fluid Mechanics and Physics disciplines) and member of GruPEFE at Universidade Paulista - UNIP. Ms. Lima holds a Bachelor degree in Physics (2008) from Pontifícia Universidade Católica de São Paulo – PUC, a Master of Science degree (2010) and a PhD degree in Science (2014) – nuclear technology – applications - from Universidade de São Paulo (USP), which is a Nuclear Technology Program of the Instituto de Pesquisas Energéticas e Nucleares (IPEN). Her research interests include experimental methods and instrumentation for elementary particles and nuclear physics and practical activities applied to Engineering Course.

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Thais Cavalheri dos Santos is currently coordinator of technical course in buildings (PRONATEC), professor of Engineering Course at Universidade Paulista – UNIP and professor of Engineering Course at São Judas Tadeu University. Mrs. Cavalheri holds a Bachelor degree in Medical Physics from Universidade de São Paulo – USP, completed in 2005. After graduating, she enrolled in a Masters in Science (Physics) Program of Physics applied to Medicine and Biology in USP, concluded in 2007. Simultaneously with the Masters course she studied a post-graduation course (latu sensu) in Business Administration – MBA in Management of Hospitals and Health Systems by Fundação Getúlio Vargas. In 2012 she got a PhD degree in Science – nuclear technology – applications - from Universidade de São Paulo (USP), which is a Nuclear Technology Program of the Instituto de Pesquisas Energéticas e Nucleares (IPEN). After completing PhD she remained as a researcher at IPEN until 2014, when she got her post-PhD.