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A CASE STUDY OF A MULTIDISCIPLINARY APPROACH FOR FACING NEW CHALLENGES FOR ADSORPTION HEAT PUMP APPLICATIONS

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ABSTRACT. In this paper, a new zeolite/silicone foam for AHP applications was evaluated as a case study of a multidisciplinary teaching approach for addressing a science education experience from the pedagogical point of view. The interdisciplinary approach promotes the improvement of scientific knowledge among different materials science disciplines allowing to develop a performing adsorbent foamed HEX. In such a context, a flipped classroom approach was identified as the most suitable method for the students to develop their individual and collaborative improvement of knowledge. Changing the classroom lesson from teaching to students learning can be an effective strategy for stimulating students' interest and learning. This approach, based on a 5E teaching model, opens up to an active and dynamic discussion phase of problem solving which, although contextualized on a practical experience, can be effectively extended in wider contexts.

1. Introduction

The term methodology has different meanings in the field of science education. Didactic and research activities, associated with it, can differs in laboratory experiences, statistical techniques of data analysis, research design and, not least, research conceptualization and context. The univocal definition of a scientific research strategy and methodology is a very complex and articulated objective, which often represents a crucial factor in achieving the educational and scientific goal (Belanger 1964).

A key aspect of the research in applied sciences is the need to define a link between the theoretical and applied value of the didactic notions and the active interaction of the learner/researchers. Through an effective learner involvement, it is possible to propose pedagogical paths aimed at integrating the different phases of research such as design of the conceptual model, design of experiment, theory, analysis and dissemination of the results. The correlation of the theoretical concepts to applied research experience effectively allows the researcher both to enhance his knowledge and to train to the assessment of applied sciences.

In such a context, this study aims to evaluate a case study of a multidisciplinary teaching approach for facing new challenges in the field of sustainable energy technologies.

Real-life problems almost never correspond to traditional disciplinary approaches in applied scientific research (Takano *et al.* 2014). The applied sciences has a key role in the evaluation of the environmental sustainability issues, representing a valid scientific reference for the development of research activity. The collaboration between the different areas of the science is, however, necessary to better understand the complex and articulated nature of the applied problems with which it is associated. In such a context, it is an important point to develop a research plan with different experimental contributions from different disciplinary contexts. That allows to offer a broader understanding and a more effective set of analysis tools to suitably address the practical problems of using the proposed technological solution (Schoot Uiterkamp and Vlek 2007). A framework of parameters, developed by several science discipline experiences, can be acquired for material evaluation and optimization (Sandberg *et al.* 2019).

In particular, in this paper, a case study referred to adsorbent composite materials for adsorption heat pumps (AHP) application was assessed.

The attended material need to have specific various performances (Martucci *et al.* 2015): to improve the mechanical and thermal stability, optimize water vapor, providing a stable and regular microstructure, guarantee high durability in real aging cycle conditions.

The materials engineering and the related technological development, are contexts in which the integration of different areas of expertise allows the development of complex systems optimized in terms of composition, functionality and morphology (Prouzet *et al.* 2008). That implied that transversal approaches could be suitable to manage a multi-level research structures.

The achievement of hybrid complex architectures implies an almost natural development of cross-disciplinary and multi-disciplinary investigation strategies offering a central role to the science and technology of advanced materials (Nicole *et al.* 2010).

Different analysis strategies can be applied to a multidisciplinary research approach (Freeman *et al.* 2014; Xiong *et al.* 2018; Ghoreishi *et al.* 2019; Sandberg *et al.* 2019). Considering the large variables involved, a decision-making procedure is required in order to determine the optimal solutions identifying the best compromise option (Xiong *et al.* 2018). Furthermore, a general framework, accounting the multi-phase variable of the investigated materials, could be configured as multidisciplinary model for the design/optimization of materials (Ghoreishi *et al.* 2019).

The proposed case study was structured based on a 5E approach (in the future section of the paper described in detail) (Bybee 2014). This procedure evidenced appropriate and understandable results in STEM (science, technology, engineering, and mathematics) disciplines (Ahmad *et al.* 2018; Bybee 2019).

The specific research field required the involvement of multidisciplinary expertise extending from synthesis, chemo-physical (morphology, vapor diffusion and permeability) and mechanical (adhesion, compression) characterization coupled with an aging and durability assessment for an its industrial applicability. The interdisciplinary approach, based on a 5E step procedure, promotes the enhancement of scientific knowledge amongst several materials science disciplines. The integrated research approach is configured as a proper procedure to develop a suitable material. Furthermore, it could be an effective and promising engineering solution to maximize chemical, physical and mechanical performances coupled to system reliability of the composite material for an industrial application such as AHP

field.
The different phases of the research activity are developed, from the conceptualization to the interpretation of the experimental results by describing a pedagogical path representative of the case in exam.

2. 5E research teaching strategy

The European Commission has promoted a pedagogical approach called Inquiry Based Science Education (IBSE) or Inquiry Based Learning (IBL). This approach is focused on the enhancement of the applied research. By means of this teaching strategy, the student has the opportunity to participate actively to the teaching experience by stimulating the formulation of questions and actions to solve problems and understand phenomena. For the application of this method, the 5E Model is usually adopted by programming the activity through the following phases: Engagement, Explore, Explain, Elaborate, Evaluate (Duran and Durán 2004; Bybee 2014).

Engagement: The activity always begins with the definition of a research context, on which students (and/or researchers) are invited to reflect and ask questions. In this phase the student must be actively involved through conceptual questions and reflections on the topic. This allows to stimulate the student's curiosity to deepen the acquired concepts. It is the most important phase when it defines the basis for an active involvement of the working units in the subsequent research phases.

Explore: In this phase the student is oriented towards experimentation, defining a possible scientific approach to achieve the theoretical objectives defined in the previous phase. The purpose of this phase is to record data, isolate variables, create graphs and analyze the results.

Explain: In this phase, the phenomena observed in the previous phase are understood and explained. The aim is to unfold the results of their explorations in a scientifically rigorous way, stimulating autonomous and group research activities on the investigated context.

Elaborate: In this phase, the understanding of the phenomena is deepened, applying the acquired concepts in a wider contexts. The data discussion allows to validate the results and understand the related physical phenomena. In this phase the effective transfer of learning and the improvement of knowledge occurs.

Evalutate: The last phase involves the creation of a final document that collects, based on self-evaluations and interdisciplinary interactions, the research findings and its interpretations.

Although the 5E model has a sequential structure, it is often necessary to go back in the didactic cycle before completing the pedagogical path. For example, several experimental campaigns or different interpretations of the results may be needed before the evaluation phase could be defined.
Figure 1 show a scheme of the 5E model. A circular interconnected structure was defined.

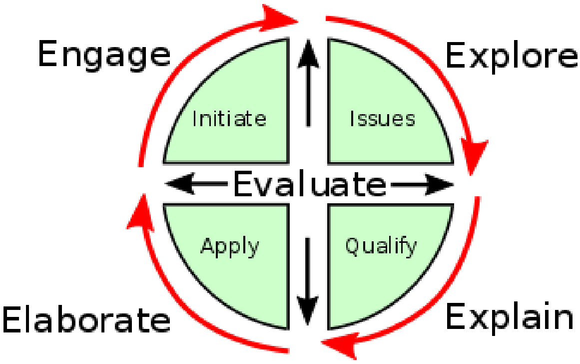

FIGURE 1. Circular scheme of the 5E Model.

A progressive sequence of the process can be globally identified (circular red arrows in Figure 1), distinguished by each phase of the scientific path. However, each phase is interconnected with the others through the evaluation phase (straight black arrows in Figure 1). This represents the cornerstone of the entire scientific research process. The formative and synergic evaluation between the different phases of the process are appropriate in this phase. This makes the present learning cycle flexible to assist the complex theoretical and experimental research development.

3. Case Study: Adsorbent material for AHP applications

The experimental project, herewith briefly described, was configured by structuring the different research phases on the basis of the 5E model. The results of this exploratory study could be used to raise awareness of an active scientific learning and enrichment approach. The units that are about to face a scientific experience can consider the use of this method in their research approach in order to enrich and to enhance the knowledge between the different units involved in the activity.

3.1. ***Engagement:*** Heating and cooling systems are widely used in industrial and comfort applications. Nowadays, the shared energy for heating and cooling demand in the global energy consumption progressively increases. Heat pumps represent the most effective industrial solution for this energy demand (Chua *et al.* 2010).
Due to the issues related to conventional energy sources, the use of energy-sustainable technologies is becoming also an industrial added value. In this concern, recent research activities on heat pumps are mainly focused on the development of new more environmental-friendly systems that have a high primary energy efficiency and are able to use various types of energy such as waste or solar energy (Demir *et al.* 2013). Thus allows to establish an interest in the current teaching and training task, highlighting the relevance of this topic for the environment sustainability.
In such a context, Adsorption Heat Pumps (AHPs) use environmentally friendly refrigerants (*e.g.*, water) and can be driven by waste heat or solar energy, thus greatly contributing to reduce emissions and fuel consumption associated with air conditioning systems (especially for residential buildings).

Basically an AHP system is constituted by four main components: an adsorber (*e.g.*, a container filled with the solid adsorbent material, such as zeolite); a condenser; an evaporator and an expansion valve. The system works by cycling alternatively the adsorbate (such as water vapor) between adsorber and condenser/evaporator (Meunier 2001; Demir *et al.* 2013).

The adsorption phenomena occurring in the adsorber act as mechanical power, so that the working fluid is forced to circulate in the cycle without any mechanical component use.

AHP systems involve adsorption phenomena between a solid adsorbent material or coating (adsorbent) and gas molecules (adsorbate) (Maeda *et al.* 2018). Unsaturated adsorbent can attract and trap, by van der Waals forces, the adsorbate molecules, by releasing energy. van der Waals bond is characterized by a weak bonding forces, therefore these trapped molecules can be simply desorbed by furnish a low energy source. Hence, the adsorption and desorption are exothermic and endothermic processes, respectively. These processes can be supplied to perform heat pumping.

In the last years, cause to improving competitiveness, research activities have been focused on developing effective AHP units characterized by multi-performing composite adsorbent coatings (Calabrese *et al.* 2017e; Kummer *et al.* 2017; Seol *et al.* 2019) to enable a more reliable and efficient sorption thermodynamic cycles.

The increasing efforts to develop a new concept heat exchanger (HEX) based on innovative adsorbent coating technologies require however a synergy of skills and experience from different scientific fields in order to guarantee a suitable result. For a successful industrial application, the knowledge sharing and multi-disciplinarily expertise are relevant aspects that are increasingly being evaluated to allow an effective design and engineering of new materials/products (Borrego *et al.* 2009; Truscott *et al.* 2010).

3.2. ***Exploration*****:** In this section, feature and capability of the current technologies were explored.

An effective design of the adsorbent heat exchanger in the AHP technology is a key point to tailor high efficiency systems. The literature reference is based on unconsolidated beds option, which is a very easy and economic design choice (Demir *et al.* 2013). In this configuration, the adsorbent material is in granules or pellets. Although, some issues related to limited heat and mass transfer capacity can be addressed by using this technology (Aristov 2013). Furthermore, a reduction of AHP performances can be evidenced due to material loss during the AHP service life.

The coated adsorber component overcomes the previous issues of consolidated beds allowing high heat transfer and good mechanical stability during service life. Thus indicates this approach as a very encouraging procedure to manufacture heat exchanger components (Calabrese *et al.* 2017e).

At the same time, however, further troubles emerge related to the low quantity of absorbent material to be added and the marked brittle behavior of the adsorbent coating that make difficult to identify the best industrial option. Table 1 compares and summarizes pros and cons of unconsolidated and coating technologies.

This makes it possible to identify new research scenarios in which the development of new materials able to optimize the performance of the AHP can be expected. This represents a discussion point for the working group from which alternative technological approaches

TABLE 1. Granular versus coated adsorbers.

	Pros	Cons
Granules	• High zeolite amount in the adsorber enhancing COP • Possibility to get high volumetric specific power • Low materials and set-up costs	• Poor heat transfer efficiency • To identify the optimized grain size distribution to limit the mass transfer resistance
Coating	• Enhance the heat transfer rate and power density with respect to a granular adsorber • Mechanical and adsorption stabilities of the coated adsorbers • Possibility of easily coat complex HEX geometries	• Low zeolite amount in the adsorber, due to the limited coating thickness • Brittle behaviour of zeolite coating

could be identified. On the basis of these inputs, a research activity aimed at enhancing effective and lasting application solutions can be developed.

In such a context, the development of an adsorbent foam with interconnected macropores for easier internal molecular diffusion can be a solution with large perspective (Figure 2) (Calabrese *et al.* 2017c). This morphological configuration could to increase coating surface area to generate a porous structure that fill the heat exchanger volume without reducing mass flow rate. At the same time, large amount of adsorbent zeolite material can be filled in the free volume between heat exchanger fins leading to possible high AHP efficiency. The matrix heed to be permeable to water vapor in order to allow the mass flow without hinder the adsorption capability of the solid sorbent added as filler. The siloxane matrix can offer suitable characteristic to act as permeable matrix in the composite macroporus structure. Furthermore it has a good chemical interaction with the silanol groups present in the zeolite surface, leading to good adhesion at the filler-matrix interphase. For such of brevity, details on this concern can be acquired in (Calabrese *et al.* 2017d).

Hybrid composite materials represent an innovative and stimulating field of basic research in which chemical science can give added value for the development of potentially effective new materials. Furthermore, thanks to the intrinsic multifunctional nature, hybrid composites are leading to trigger new innovative industrial contexts (Schottner 2001; Piperopoulos *et al.* 2017).

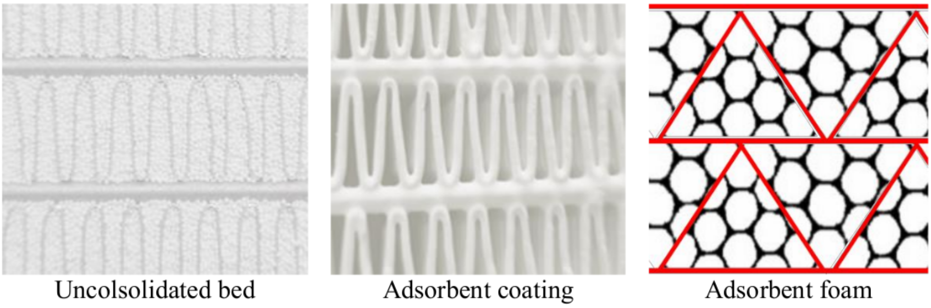

FIGURE 2. Visual comparison of unconsolidated bed, coating and foamed adsorbent materials.

For the design of the experimental campaign it must be taken into account that the investigated material must have specific characteristics that need to be verified in order to adress its applicability in AHP systems (Freni *et al.* 2013).

For these zeolite silicone composite material a multidisciplinary approach is required. The permeable silicone matrix containing inorganic zeolite fillers need to be synthetised and characterized in order to offer some specific key properties (Belkhair *et al.* 2015), *e.g.*, i) zeolite adsorption performances, ii) polymers physical and mechanical performances and stability iii) morphologicial homogeneity. In particular, in this phase a possible experimental approach to achieve the theoretical objectives previously defined can be briefly ordered as in the following:

- Material homogeneity;
- Mechanical performance under static and dynamic loads;
- Adhesion with the substrate;
- Water vapor adsorption;
- Mechanical and hydrothermal durability.

In order to achieve these objectives, the integrated design of morphological (Calabrese *et al.* 2017a), mechanical (Calabrese *et al.* 2017b), adsorption (Calabrese *et al.* 2018) and durability in real operating conditions (Calabrese *et al.* 2019), represent the most effective strategy for assessing their application capabilities.

The integrated study of these properties, based on an interdisciplinary collaboration of several units, allows to define, in a targeted way, the possible effectiveness of the applied experimental approach.

3.3. ***Explanation**:* In this phase, the explanation of the physical phenomena that oversee the process takes place. The combination of several experimental investigations allows to better interpreting results by correlating them specifically with the chosen application. The integrated information acquired by different analysis techniques can allow the definition of the most effective experimental batch. The use of multiple variable analysis systems can often be a valid support to better discern the significant parameters of the process (Khaskhoussi *et al.* 2017; Ghoreishi *et al.* 2019; Sandberg *et al.* 2019). Otherwise, as reference, a simple approach to compare results acquired from different sources can be to define a normalized efficiency index.

Defining reference threshold values, for each property, identified as suitable for the chosen application, it could be possible to assess the goodness of the coatings, estimating an Efficiency Index (EI) as:

$$EI = \frac{M_{evaluated} - M_{threshold}}{M_{threshold}} = \frac{\Delta M}{M_{threshold}} \tag{1}$$

$EI < 1$ indicates a low efficiency of the coating in this specific property. $EI > 1$ is referred to high goodness results. A topological plot is the output of this analysis. Figure 3 shows a reference plot where some performances (pull-off, peel test, impact, and adsorption) are compared for three different batches. The plot visually shows the safe and unsafe use conditions, easy highlighting the suitability of the C batch. Although Batches A and B evidenced a more effective pull-off strength, they not achieved the expected performances in terms of pull-off and adsorption test. Only C batch exhibits reliable performances ($EI > 1$) in all performed tests.

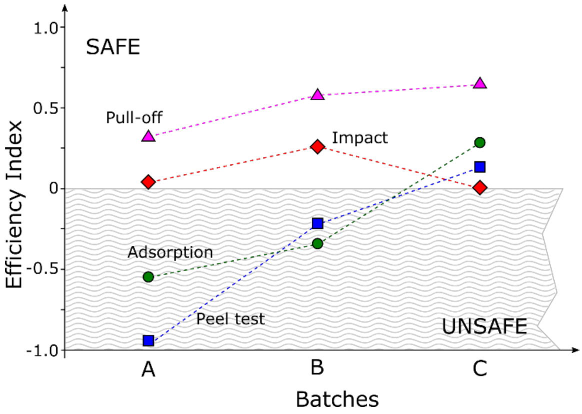

FIGURE 3. EI parameters for some tests performed on different coating batches.

3.4. ***Elaboration*:** This is the key section of the learning process of the phenomena that oversee the material behavior. This phase engages researcher units in a virtuous active learning process through, according to **Freeman et al.** (Freeman *et al.* 2014), a two level steps:

- A higher-order group thinking, indicated as “first-generation” of research in this field;
- a “second generation” research that evolves based on a comparative analysis with literature references.

The assessment of the effectiveness and efficiency of the material stimulates the development of interpretative models of the phenomena. These models serve to better understand and interpret the acquired experimental results, generalizing the concepts to wider interpretative contexts. In this phase, the transfer of the explicit knowledge during the developed experimental path takes place. In the proposed case study, the hypothesis to use a macro-porous foam to allow a high mass transfer capacity during the water vapor adsorption and desorption process was validated by the thermo-gravimentric adsorption tests. Figure 4 compares the water vapor uptake during adsorption test among pure SAPO-34 zeolite powder and a low and high zeolite content composite foam (37 wt.% and 70 wt.% respectively).

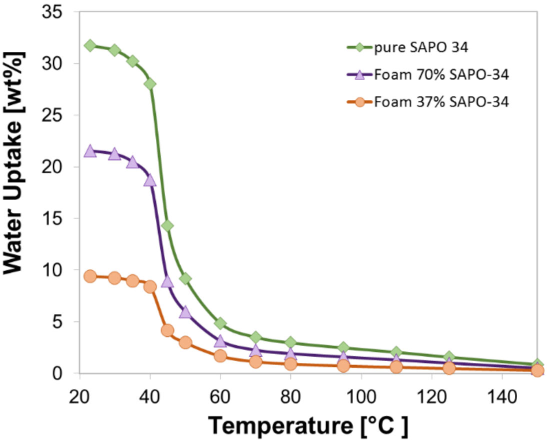

FIGURE 4. Comparison of water vapor adsorption, in isobaric conditions ($P_{H2O=}11mbar$), among pure $SAPO-34$ zeolite and low and high zeolite content foam ($37wt.\%$ and $70wt.\%$ respectively).

The isobaric curves were measured at P_{H2O} of 11 mbar in the temperature range of 30–150°C.

All curves have a typical sigmoidal shape with a relevant increase in water uptake at about 45°C. As expected, the composite foams shoed a water uptake always lower than pure SAPO-34 This is related to the specific amount of zeolite powder filled in the foamed matrix.

In exemplum, he maximum water vapor adsorption for foams with 70 wt.% of zeolite is about 21%. Taking into account that the pure SAPO-34 showed a maximum adsorption of 31.7%, these results indicate that about 98% of the zeolite embedded in the foam is able to perform adsorption and desorption cycles. The macro-porous siloxane matrix acts as binder among the zeolite filler, guarantying good mechanical stability, without hindering the adsorption performances of the active zeolite filler.

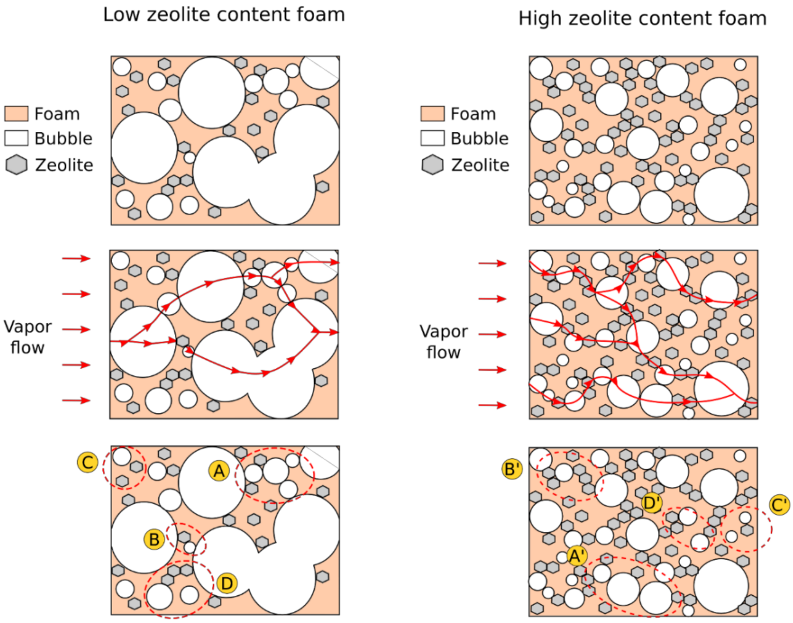

FIGURE 5. Scheme of morphology and water vapor flow pathways in low zeolite (left) and high zeolite (right) composite foams. (modified from (Calabrese *et al.* 2017a)).

Coupled with the morphological and mechanical suitability of the material, it is possible to interpret the results by proposing, for example, the possible diffusion paths that take place in the tested composite foams (Figure 5).
In particular, it is possible to discriminate a different behavior for low or high content zeolite foams.
For the former, the vapor flow is guaranteed by the intrinsic macro-porous interconnected morphology of the foam. The latter composite foam has a slight different macroporus structure. The foam is constituted by small and not interconnected bubbles. Sometimes, some neighboring bubbles could be identified. Although high adsorption/desorption efficiency was observed, for all batches (Calabrese *et al.* 2018). Therefore the water vapor flow is ensured by two contributes i) a main porosity coupled to complex microscopic paths in the composite matrix; ii) the vapor permeability of the siloxane binder plays a relevant role in the adsorption efficiency of the composite material. In fact, the triggering of preferential pathways for the water vapor adsorption/desorption process is favored by the vapor high permeability of the matrix itself (Robb 1968). Furthermore, the graphic support allows to better understand in an intuitive and simplified way the complex dynamics that take place. This also allows to define possible new research pathways, proposing future improvements based on the outcomes of the proposed approach.

3.5. ***Evaluation**:* The last phase of the activity is related to the final report, presentation or paper that summarize the research findings of the activity. This step encourages researches to assess their understanding and abilities, sharing ideas and opinion. That allow also the research supervisor to better address the research topic toward new frontiers.

4. Flipped Classroom

In such a context, a flipped classroom method can be addressed as a proper strategy to stimulate the individual and collaborative improvement of knowledge in the classroom students. To switch the classroom lesson from teaching to students learning can be a suitable approach to favor the student interest and learning. This strategy can trigger a dynamic and stimulating discussion phase of problem solving which, although contextualized on a practical experience, can be effectively extended in wider contexts. This learning method is well suited to a didactic experience, as in the case study reported in the article, in which the laboratory experience is a key point.

A conventional didactic approach can be schematized in two phases: i) a first phase of explanation carried out by the teacher in the classroom ii) a second phase where students complete the learning process by carrying out homework individually at home.

Vice versa, in the flipped model the didactic approach is inverted ("flipped"). The first phase is based on the autonomous learning by each student at home. In this phase, the use of multimedia tools can be effective and productive to stimulate the student interest. The second phase provides that the lessons are carried out by the teacher to conduct a personalized teaching experience strongly oriented to extend in practice the concepts acquired during the first learning phase. The classroom experiences will be enhanced by the collaboration and cooperation of the students who will represent key aspects of the teaching experience.

Consequently, the flipped model imposes a reversal of roles between classroom teacher and students. Also the pedagogical control of the process is reversed from the teacher to the students who become the central point of discussion. This implies that the subject of the learning process is the students, who are stimulated to assume greater autonomy and responsibility regarding their own training process. The teacher assumes the role of moderator aimed at leading the class in order to guarantee the educational success of the experience. The teacher has the relevant task to promote a suitable individual access to the didactic contents, preserving the autonomy of each student in managing the learning and self-evaluation times, during the first phase. At this stage, the teacher must ensure the students technological equity, guaranteeing that all students have adequate technological equipment, such as an electronic device (*e.g.*, PC, laptop or tablet) and an internet connection. In such a contest, a productive use of the social media is favored. Similarly, during the second phase of the process, the teacher must encourage and address the students to a personal research, to the collaboration and sharing of the acquired knowledge. Consequently, the flipped teaching approach is aimed to enhance the digital resources and social networks. This has a beneficial effect on students who understand that the impact of social media can be educational and formative and not exclusively playful. The inverted educational path radically transforms traditional learning moments preserving, anyway, a solid educational base. To increase the classroom collaborative learning is an added value aimed to improve the exchange of ideas among students by promoting their interaction and integration, each one with a specific but interdependent role, in the development of a shared common project. In the study experienced in this paper, the student need to acquire the basic knowledge concerning the sustainable energy technology extending their notions to adsorption heat pumps, focus of their classroom experience. These latter will be scheduled in five modules according to 5E model approach. For each step a preliminary home study experience able to acquire the specific knowledge is recommended. The teacher, for each sub-step, could plan specific multimedia educational paths that can be used by students as a stimulus to start their own research. During the classroom experience individual and group challenges will be periodically scheduled to assess the level of response of the class to the didactic experience in progress.

Thanks to the integration of the 5E model with the flipped teaching model, a final evaluation may not be foreseen, considering that the answer on the effectiveness of the didactic method is ascertainable from the tangible elaborates and reports carried out by the student class during the development teaching course.

5. Conclusions and final remarks

The main goal of this paper is to propose a multi-step decision procedure to activate a teaching-learning loop on classroom based on a practical experience on materials design in a sustainable energy field. Although this approach is preliminary referred to material science field, it offers a valid support for a rational and practical material choices in this field. For a deeper and different understanding of the material-technology relationship, it should be necessary to add other peculiar parameters such as adsorption heat pump service life or maintenance costs. This approach could complete the material knowledge in order to define a more appropriate material choice in relation to the sustainable energy component life cycle including furthermore the attended end-of-life scenario of adsorbent composite material. The proposed approach is referred to a single case study for a specific application but it could be extended to other research fields where a multidisciplinary experience is an added value. Future study focused comparable approaches could allow to develop more exhaustive and comprehensive decision approach. The interdisciplinary approach, based on a 5E step procedure, promotes the enhancement of scientific knowledge on this practical case study. In this teaching experience, a flipped classroom approach was identified as a potentially more effective method to stimulate students individual and collaborative learning. Proposing upside-down teaching-learning experiences can prove to be an effective strategy to activate curiosity, interest with beneficial effect on students learning.

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