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Article

# Incorporating Augmented Reality Tools into an Educational Pilot Plant of Chemical Engineering

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**Abstract:** Chemical Engineering courses are often designed to be divided into two types of lessons: lecture and experimental. In the second one, students develop the knowledge in a hands-on way by attending a pilot plant equipped with different instruments. Hence, a thorough understanding of the different unit operations is needed and, therefore, the implications of changing the operational variables in a process. In this context, the use of new digital technologies is emerging as support tools with the aim of both improving the learning and the motivation of students. Specifically, Augmented Reality (AR) provides a modified physical environment overlaid with multimedia content in the form of text, graphics, video and/or audio. Thus, the incorporation of AR systems in the learning of science has proven to be useful, because it can present multiple benefits for students and teachers related to the improvement of spatial abilities, the increase of memory retention, the decrease of cognitive overload, and a boost in student motivation. This study has carried out a search for resources, projects, software, and applications to implement AR-based tools in the experimental sessions of a Chemical Engineering educational pilot plant. Based on all the information found, several AR projects were proposed by the teachers. Later, some of them were selected according to previously defined criteria and implemented as educational tools for students in the course called *Experimentation in Chemical Engineering I*. Finally, this tool was evaluated through subsequent post-surveys, being very positively rated by both students and teachers, mainly in the items related to helping to understand concepts or the operating procedures of the equipment.

**Keywords:** Chemical Engineering education; educational immersion; augmented reality; educational pilot plant; teaching tool

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## 1. Introduction

The High Education Degree in Chemical Engineering has applications mainly in an industrial context, which includes the design of processes that turn raw materials into valuable products [1,2]. Thus, Chemical Engineering courses are often designed to be divided into two types of lessons: lecture and experimental sessions. In the experimental sessions, students develop the knowledge in a hands-on way, attending a pilot plant equipped with different instruments. Consequently, a thorough understanding of the different unit operations is needed as well as the implications of changing operation variables in a process. Many of the processes involve complex operations and some of these concepts are difficult to grasp for many students, who sometimes remain passive during the experimental sessions.

In the last decade, the utilization of new digital technologies in education has been advocated in the scope of the European Commission in the Agenda for the Modernization of Europe's Higher Education Systems [3], with the focus on learning (instead of teaching) and motivating, together with student engagement, in the different courses [4]. Even more, recently, in the new scenario brought about by the COVID-19 pandemic, virtuality, online spaces, and digital resources have been the main drivers of knowledge [5]. This situation has forced the transition to online/virtual learning and teachers around the world have realized the importance of implementing such technologies in the teaching curriculum [6,7]. Examples of digital resources include immersive tools, such as Virtual Reality (VR), Augmented Reality (AR), or Mixed Reality (MR) [8–11].

While VR immerses the user in a fully digital environment, AR can provide a modified physical environment, overlaid with multimedia content in the form of text, graphics, video and/or audio. Both types of content can be placed into a student's real-time environment allowing users to experience a mixed sensorial environment [12]. This significant innovation truly allows the world of technology to connect with the educational world. VR implies the use of special glasses and is considered more immersive and AR is usually displayed on a smartphone or tablet, so it only complements rather than replaces reality [12,13].

In relation to the AR implementation, two major types of image-based can be used to activate the AR content to be shown: (i) marker-based AR, and (ii) markerless AR. The markers can be embedded into educational material, which is used to produce supplementary information when scanned by the device camera. Hence, when using marker-based AR, the user must be pointing their device camera towards the marker to be able to see the multimedia content. In this way, a predefined 2D image, QR code, or 3D object could be used as a 'marker', in order to recognize the position of the virtual objects [14] and so link information to objects, including scientific instruments. Thus, for applications where total immersion is not well justified, the incorporation of AR systems has proven to be useful, due to its ability to present multiple benefits for students and teachers.

In this context, AR technology has significant potential as a tool that can easily be used by students and teachers of all levels to visualize and interact with equipment and processes. A large number of AR applications have been designed in a wide variety of learning realms and for all educational levels, including at the university level [15]. Numerous studies have examined the effects of AR on the way students learn and perceive different concepts [16,17]. Specifically, for STEM education (Science, Technology, Engineering, and Mathematics) the use of AR technology has increased significantly in the past few years. Depending on the field of engineering, AR applications have demonstrated diverse purposes such as visualizing simulation results [18], overlaying additional information [19], or even enhancing on-site operations by providing real-time data [20]. Moreover, AR has been applied in laboratory lessons in engineering courses to help students learn about machinery operation [21], thus, working as an interactive experimental manual [22], creating a remote laboratory tool that students can utilize without physically being present in schools [23], or building an interactive and collaborative learning environment [24]. A recent review in this matter [25] summarized studies involving AR in education from 2011 to 2016, highlighting that only about 15% of reports were from the fields of engineering, manufacturing, or building. This fact was further reiterated by other work [26], which states that these fields were explored up to 2018. This clearly indicates that AR technology in engineering education is still in its initial phases of development with greater potential for further exploration.

However, it should be noted that research on AR in education is evolving rapidly [27,28] as it helps boost student achievement compared to traditional teaching methods [29]. For example, AR could provide an extra visualization of a situation, process or equipment, exposing students to the scenario without the use of potentially dangerous machinery [30]. Data from several studies suggest that the learning benefits of AR are related to the improvement of spatial abilities, the increase in memory retention, the decrease of cognitive overload, and the boost in learners' motivation [31–34]. Additionally, AR can positively affect the academic performance and achievement of students [35–40].

Although the educational value of AR is confirmed nowadays, this technology also has its limitations and it should be noted that its use in educational settings also comes with some challenges. From a pedagogical perspective, it may not always be evident how to integrate educational content and AR technology [31,40]. Different studies have identified drawbacks that hinder its broader implementation [18,31,32,34]. Some of these can be listed as follows: (a) a limited interaction between the user and the digital environment; (b) a cognitive overload that can be distracting and hinder the transference of an experience to different settings, by the lack of support for good compatibility between platforms; and (c) a lack of well-designed interfaces. In fact, certain studies have found that students focus predominantly on procedural details rather than understanding and connecting theoretical knowledge with other aspects of practical experiments [41,42]. As a result, further research is needed in order to develop quality educational resources that leverage the advantages of this tool [34].

Thus, in the framework of the activities planned in a Teaching Innovation Project funded by the University of Cádiz, a search for AR resources, projects, software, and applications has been carried out. The aim was to implement AR-based tools in the experimental sessions in the educational Chemical Engineering pilot plant. Based on all the information found, the teachers proposed several projects based on AR with markers. Later, one of them was selected according to defined criteria and it was implemented as an educational tool for students in the course called *Experimentation in Chemical Engineering I* (Third year Degree in Chemical Engineering). Finally, this tool was evaluated through subsequent post-surveys.

## 2. Materials and Methods

First, it could be convenient to establish the meaning that authors assign to several terms used in this text. If their meanings are not clarified, given the breadth of the semantic content of these words, the reading of the article may result in confusion. These terms are the following:

- Augmented reality-based teaching tool: The combination of digital resources (photos, graphics, figures, animations, audio, videos, etc.) with live images of physical reality in order to produce an educational tool. The combination of both entities (digital and physical) is managed by appropriate software, which is run on a specific device operated by the student.
- Prototype: Here, it refers to any AR-based teaching tool that is under construction. Of course, it has not been tested with students until that moment.
- Digital resources: The set of digital objects (photos, graphics, figures, animations, audio, videos, etc.) that we can combine with physical reality to produce AR material. Actually, it includes all resources that we can find in digital reality (virtual reality).
- Device: Here, it refers to any electronic apparatus equipped with a camera (PC, laptop, tablet, mobile phone, etc.) that is able to run the computer programs for the generation of AR products.
- Software Development Kits (SDK): The specific software that is necessary to develop the computer programs, which can generate the AR products. The SDK may be installed on a computer or may be run on a server. The generated programs can be executed on other devices, if applicable.
- App: Simple computer application that must be installed on the device on which you want to run the AR teaching tools. The SDK must generate files that can be read by that app. The developer of the SDK usually supplies a suitable app in the proprietary store.
- Target: Any physical element that the device must recognize before launching a specific piece of the AR-based tool. It can be an image focused by the camera, a sound registered by the microphone, a position or vibration detected by the gyroscope, or even any particular GPS position. If the target is a specific image drawn by the programmer, then it is usually designated as a 'marker'.
- Augmented Reality Project: Here, it is assigned to any idea of the combination of resources, targets, and procedures, clustered in a file to offer the students a specific AR-based teaching tool. The project starts with the formulation of the idea and ends with the operative use of the tool in the classroom. Of course, not all projects come to the end.

In Figure 1, the interrelation between the concepts defined above is shown.

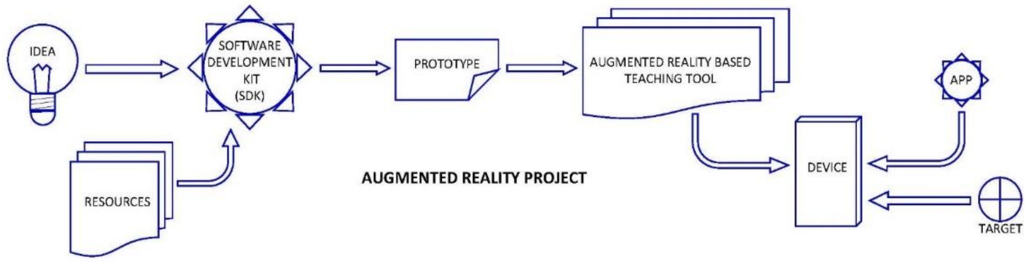


**Figure 1.** Links among the concepts related to the Augmented Reality project.

Regarding the method kept in all the AR projects that have been developed in this work, all of them traced the stages that follow:

(1) Search for resources and evaluation;
(2) Search of SDKs and selection;
(3) Proposals and selection of prototypes;
(4) Prototypes development;
(5) Implementation and use of the AR-based teaching tool;
(6) Assessment of the AR-based teaching tool.

The next subsections fully explain the methodology followed in each of these stages.

### 2.1. Search for Resources and Evaluation

In this step, the method consisted of developing internet searching for audio, videos, animations, etc., related to Chemical Engineering teaching. Thus, several search engines and keywords were used. Some of them were the following: AR Chemical Engineering, Educational Chemical Engineering, AR Pilot Plant, Educative Material for Chemical Engineering, etc.

Once the most important sites related to Chemical Engineering education and AR education were located, the available information was reviewed. If it was thought to be interesting, it was downloaded to the database. Later, all the members of the project team (a teacher group) were consulting and assessing the material in this database for several weeks. At the end of this period, all the material loaded into the database had been evaluated. In a final assessment session, the teachers held a meeting to discuss the relevant aspects of the collected material and, specifically, the suitability of using each piece in the AR projects. This implied their potential use in the educational pilot plant of Chemical Engineering.

### 2.2. Search of SDKs and Selection

As in the previous stage, the method followed was based on internet searching, with different search engines and keywords for SDKs. Some of these words were the following: AR Software, AR Computer Program, AR Application, AR Software Development Kit, etc. After the search, the most important sites were located and visited for extracting the most relevant information. Again, during several assessment sessions, the teacher group revised all the information on each software item and decided on the suitability of each option. This selection involves the revision of the following aspects: (a) versatility of the software (number of different types of files that can be run in devices and number of different types of devices that can run the files); (b) the facilities offered with the pack (number of different types of resources supplied); (c) the access mode to the software (local or remote); as well as, of course, prices, custom services, etc.

### 2.3. Proposal and Selection of Prototypes

In this stage, the teachers analyzed the possibilities of incorporating own-made AR-based teaching tools into the learning procedures of the Pilot Plant (Degree in Chemical Engineering), with the aim of carrying out a preliminary screening that would allow defining which experimental equipment and experiences were more suitable to applying AR.

As a result, it was considered appropriate to develop a limited number of prototypes. All the prototypes for experimental equipment were used by a large number of students. Other criteria considered for the selection of prototypes were the following:

- Equipment Scale: Consideration of whether the equipment scale (lab or pilot) favors or obstructs the elaboration and use of the AR-based teaching tools.
- Accessibility: Ease of placement and use of the physical markers in the positions that are necessary.
- Availability: Assessment of the number of available resources on the internet and databases that are not self-produced by the authors.
- Customizability: Ease of incorporating resources from own production.
- Reusability: Possibility of using AR-based teaching tools with minimal changes in other similar experimental equipment in the Pilot Plant.
- Specificity: Intrinsic benefit of the didactic resource for learning in relation to the content of the subject where the AR-based teaching tool was applied.
- Integrability: Adaptability of the resources used to the real morphology and size of the physical objects.

### *2.4. Prototypes Development*

Once the prototypes were selected according to the criteria specified in the previous section, the teacher team worked with the ROAR® platform as the SDK for the development of the AR-based teaching tools: https://theroar.io (accessed on 10 December 2022). Two levels of tests were established during the development of the prototypes:

(1) At the level of the teaching staff. Several groups of 3–5 teachers tested the rough versions of the prototypes to assess the technical utilization of the prototypes and their adequacy to the didactic objectives of the courses.

(2) At the level of a small group of collaborating students. The previous test level was extended with the participation of some selected students to provide the point of view of the 'end user' of the prototype from a technical perspective (not didactic). After this evaluation, only one prototype was chosen for full development and to be used at the general student level.

### *2.5. Implementation and Use of the AR-Based Teaching Tool*

Among the AR prototypes proposed, only one of them was finally selected to be implemented and to be put into operation with the students during the sessions in the educational pilot plant. For this purpose, firstly, the group of teachers placed the markers on the experimental equipment (i.e., a continuous distillation apparatus) in a visible and accessible area for the students, carrying out different tests to verify the correct operation of the AR-based teaching tool developed. Then, the students who operate and work with the experimental equipment in the sessions of the course called *Experimentation in Chemical Engineering I* (Third year, Chemical Engineering Degree) were informed by the teachers of the possibility of downloading the ROAR® application on their devices (smartphones and/or tablets), as well as the necessary steps to access the resources integrated into it. In this way, the students who gave their consent to participate in this study tested the resources implemented, being able to freely visualize the AR-based teaching tool during the regular sessions.

### *2.6. Assessment of the AR-Based Teaching Tool*

To assess the AR-based teaching tool developed and implemented during the pilot plant sessions, post-surveys were carried out anonymously by the participants in this study, both students and teachers. Thus, the group of teachers from the Chemical Engineering area involved in the development of this work (14), with extensive teaching experience, discussed and selected the questions that should be included in the questionnaires. In this way, other surveys evaluating resources based on immersive technologies in Chemical

Engineering or similar STEM disciplines (Biotechnology, Bioprocesses, and Biochemical Engineering, etc.) were used as a guide for the elaboration of these surveys [43–45].

Later, the students (44) who tested the resources used in the pilot plant sessions were invited to answer the paper survey anonymously. As presented in Table 1, the questionnaires included specific questions with the aim of determining the usefulness of the AR resources generated as a pedagogical tool and their assessment, as well as identifying areas for improvement. Different types of questions were included in the survey, which included rating responses on a scale of five (strongly disagree to strongly agree) or a ten point Likert-scale.

**Table 1.** List of questions proposed to the students in the post-survey.

| No. | Question | Type |
|---|---|---|
| 1 | Quality of the videos and/or images shown | 10 point Likert-scale |
| 2 | Easy to identify the objectives to be explored | |
| 3 | Usefulness of videos or images shown with AR to understand an aspect of practice equipment | |
| 4 | Usability with my mobile device | |
| 5 | Useful for enhancing student motivation | |
| 6 | Useful to better remember concepts | |
| 7 | Useful for fostering self-learning in student | |
| 8 | I would like to see this type of AR-based teaching tool in more sessions | 5 point Likert-scale |
| 9 | It would be great to use AR in all courses of the Degree and/or Master's | |
| 10 | It is an excellent tool to support teaching in pilot plant | |
| 11 | It is fine as a curiosity, but it is not useful for anything else | |

Likewise, after the development and implementation of the AR-based teaching tool, teachers were invited to answer a survey to share their opinions. This survey asked questions with the aim of determining their point of view on the AR resources generated in terms of usefulness, improvement, and overall assessment (Table 2). The survey included different types of questions, with responses on a scale of five (strongly disagree to strongly agree) or a ten point Likert-scale.

**Table 2.** Teachers survey statements about AR-based generated teaching tools.

| No. | Question | Type |
|---|---|---|
| 1 | Useful for encouraging the student to learn the course | 10 point Likert-scale |
| 2 | Useful to understand some concepts and operation of the equipment | |
| 3 | Useful to better remember concepts | |
| 4 | Useful for fostering self-learning in student | |
| 5 | I think that in some sections of the subjects related to my teaching, it would be interesting to carry out this initiative | 5 point Likert-scale |
| 6 | It would be great to use AR in the orientation days related to the High School and/or Master's | |
| 7 | It is an excellent tool to support teaching, dissemination, or diffusion. | |
| 8 | It is fine as a curiosity, but it is not useful for anything else | |

Finally, the data and answers collected from all post-surveys, both from students and teachers, were analyzed using the statistical plugging of Microsoft® Excel® 2016.

## 3. Results and Discussion

The results obtained in each stage of the project, which were mentioned in Section 2, are explained in the following subsections.

### 3.1. Search for Resources and Evaluations

The search for digital resources for Chemical Engineering teaching, as described in Section 2.1, resulted in abundant material related to different industrial equipment and unit operations. Thus, many videos and animations explaining the operation or the handling of industrial equipment were found, such as distillers, extractors, reactors, heat exchangers, etc. However, after a detailed evaluation, it was considered to be very complicated to integrate most of them into the AR projects. The reason was that none of them completely met all the conditions required for audiovisual material to be included. For example, some of them did not correspond exactly to the real equipment in the educational pilot plant, and some others did not show the exact information that was wanted to be communicated. In many cases, the material did not meet the required quality level. This last condition was very important to capture the student's attention from the first moment and to maintain their interest.

Despite a very high quantity of audio-visual material related to Chemical Engineering education, it was decided not to use most of it in the projects. Only on some occasions was the material of high quality and high specificity and thus incorporated into the teaching program resources. As a consequence, there was a need to develop our own audiovisual resources for the AR projects, with the desired information, and of the desired quality.

### 3.2. Search of SDKs and Selection

The internet search performed in this stage resulted in the list of software shown in Table 3. This registered the most important features of each element, useful in the later selection stage. As can be seen, despite this list not claiming to be exhaustive, it contains a high number of items. This makes us think that there is a lot of activity nowadays in the creation of AR materials, not only for commerce but also for other purposes, including education. Many of the products are open-source software and can be downloaded and run easily, without any cost. Moreover, users of this type of program normally share resources and projects in social networks, specifically developed for that aim, where assistance from peers can also be gained. Other SDKs are proprietary types. These producers offer many facilities in addition to access to the software, for example, the possibility to download audio-visual resources of high quality or the possibility to contact expert assistance.

Most of the software listed in Table 3 shows enough versatility to manage different types and formats of files or to use different models or configurations of devices (Android®, iOS®, Unity®, Unreal®, Blackberry®, etc). There is a reduced number of dedicated software.

One of the problems found in selecting software from the list is that developers include a high grade of dynamism in their products, and therefore, the features of the downloaded product in change over a short time. Of course, even when it could be considered that incorporating new possibilities into the software is a good point, changes in the software are not so good during development. Some products have even been canceled within one year of launching. Of course, too much dynamism in software can cause some mistrust in the end users. Thus, at the end of the stage, it was preferable to rely upon software that had shown a long stable career.

**Table 3.** List of the most important Augmented Reality Software Development Kits. The features shown here were registered on the date of visiting the site.

| Platform/SDK | Developer | Founded | Accessibility | Running Mode | App Device [1] | Versatility [2] | Facilities [3] |
|---|---|---|---|---|---|---|---|
| A-Frame | MIT | 2019 | Open Source | Web Server | All standards | +++ | +++ |
| Amazon Sumerian | Amazon | 2022 | Proprietary | Web Server | All standards | +++ | + |
| Apertus VR | Several universities | 2016 | Open Source | PC Local | All standards | +++ | +++ |
| AR.js | MIT | 2021 | Open Source | Web Server | All standards | + | + |
| ARCore | Google | 2018 | Proprietary | PC Local | All standards | ++ | + |
| ARGear | Seerslab Samsung | 2020 | Proprietary | Web Server | All standards | +++ | +++ |
| ARKit | Apple | 2020 | Proprietary | PC Local | iOS | + | ++ |
| Arti AR | Arti | 2020 | Proprietary | Web Server | Android, iOS | + | + |
| ARToolKit | GNU LGPL | 2000 | Open Source | PC Local | All standards | ++ | ++ |
| Augment | Several enterprises | 2011 | Proprietary | Web Server | All standards | ++ | ++ |
| Aurasma (HP Reveal) | HP | 2011 | Proprietary | Web Server | Android, iOS | ++ | ++ |
| Blippbuilder | Blippar Group | 2021 | Proprietary | Web Server | Android, iOS | + | +++ |
| BLUairspace | RalityBLU | 2021 | Proprietary | PC Local | iOS | + | + |
| Broadcast AR | Inde | 2020 | Proprietary | PC Local | All standards | +++ | + |
| DroidAR | Bitstars | 2010 | Open Source | PC Local | Android | + | + |
| Effect House | Tik Tok | 2022 | Proprietary | PC Local | Android, iOS | + | + |
| Face AR | Banuba | 2016 | Proprietary | Web Server | Android | + | + |
| Hololink | Hololink | 2021 | Proprietary | Web Server | Android, iOS | + | ++ |
| Kundan AR | Kundan Inc. | 2014 | Proprietary | PC Local | Android | + | + |
| Layar | Blippar Group | 2021 | Proprietary | PC Local | Android, IOS, BlackBerry | ++ | ++ |
| Lens Studio | Snap Inc. | 2017 | Proprietary | PC Local | Android, iOS | ++ | ++ |
| Meta Spark Studio | Facebook | 2019 | Proprietary | PC Local | Android, iOS | + | ++ |
| MindAR | MIT | 2021 | Open Source | PC Local | Android | + | + |
| Oculavis SHARE | Oculavis | 2020 | Proprietary | Web Server | Android, iOS | + | + |
| Open Illusionist | Open Illusionist | 2015 | Open Source | PC Local | Android | + | + |
| OpenSpace3D | OpenSpace3D | 2016 | Open Source | PC Local | All standards | +++ | +++ |
| PlugXR | PlugXR | 2020 | Proprietary | Web Server | Android, iOS | ++ | ++ |
| ROAR | Roar IO Inc. | 2016 | Proprietary | Web Server | All standards | +++ | +++ |
| Scope AR | Work Link | 2011 | Proprietary | PC Local | All standards | +++ | ++ |
| Vuforia | PTC Inc. | 2020 | Proprietary | PC Local | All standards | ++ | + |
| WakingApp | WakingApp | 2019 | Proprietary | Web Server | All standards | +++ | +++ |
| Webcam Social Shopper | Zugara | 2013 | Proprietary | Web Server | All standards | + | + |
| Wikitude | Wikitude | 2021 | Proprietary | PC Local | All standards | +++ | +++ |
| ZapWorks | Zappar | 2017 | Proprietary | Web Server | All standards | +++ | +++ |

[1] Type of device allowing running of the app. All standards = Android, iOS, Unity, Unreal, BlackBerry, etc. [2] The ability to manage many different file types, not only for audio-visual files but also for executable ones. [3] The list of services offered with the software. For example, access to resource databases, user advice, storage servers, etc.

As it was previously mentioned, another important point for software selection was the cost. In general, the most expensive products supply more facilities and quality, and vice versa. Thereby, some developers not only offer their software but also advice in developing your project or the total development of it, as a tailor-made and turn-key project. Due to the interest in exploring the possibilities of AR projects in the teaching of Chemical Engineering and analyzing the difficulties that this implies, rather than the end product, it was preferable to expand the search for a less expensive product.

As can be seen in Table 3, another important point in the software selection is the ability to manage many different types of files. This aspect is important not only for the type of audio-visual files which you might want to include in the projects but also for the type of executable files that you might want to create. Likewise, it is important to have the possibility to use the developed AR teaching tool on many different devices, as the students could use a variety of devices and gadgets to access it. This detail became a more important point than was considered at the beginning. Obviously, this point is not relevant in the development of AR-based tools for museums or institutions, where the audience will only use the specific devices supplied by the company.

Definitively, after a detailed review and consideration of all the software in the list, including some features not registered in this article as after-sales guarantees, speed of service, etc., the teacher team decided to choose the software termed ROAR®, from Roar IO Inc. (New jersey, NJ, USA), as the SDK to be used in this work.

### 3.3. Proposals and Selection of Prototypes

As was mentioned in Section 2, a selection of prototypes from twelve proposals was made. Table 4 shows these twelve AR-based projects, indicating the course and the experimental equipment to be involved, as well as an analysis of its main characteristics (see Section 2.3).

**Table 4.** List of considered options and criteria for the selection of the prototypes.

| Course | Experimental Equipment | AR Project Proposal | Criteria | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Equipment Scale | Accessibility | Availability | Customizability | Reusability | Specificity | Integration |
| **Chemical reaction engineering** | Complete stirred tank reactor | Non-ideal flow model visualization | + | + | + | − | − | + | − |
| | Test tubes | Molecule reaction model | − | + | + | − | − | + | − |
| **Plant practice in chemical engineering I** | Batch distillation | Pop-up information labels, reflux splitter operation and inner space boiler visualization | − | − | + | + | − | + | + |
| | Continuous distillation | Inner space column visualization, pre-heat exchanger operation and electro valve operation | + | + | + | + | − | + | + |
| | Gas-liquid absorber | Pop-up information labels and magnetic centrifuge pump operation | + | − | + | − | − | + | − |
| | Falling film evaporator | Inner space column visualization and boiler operation | − | + | + | − | − | + | − |
| **Plant practice in chemical engineering II** | Gas-solid catalytic reactor | Pore diffusion and reaction visualization | + | + | + | − | − | + | − |
| | Gas-liquid absorber with reaction | Interface diffusion model visualization | + | − | + | − | − | + | − |
| | Several equipment | Peristaltic pump operation | + | + | + | − | + | − | − |
| **Fluids flow** | Pressure load losses in pipes | Bourdon manometer operation | − | + | + | − | + | − | − |
| **Heat transfer** | Concentric tubes heat exchanger | Pop-up help about valves disposition for different contact ways (direct and backflow) | + | + | − | + | − | + | + |
| **Separation basic operations** | Open batch distillation | Inner space boiler visualization | + | + | − | + | − | + | + |

The selection of prototypes was focused on the ‘specificity’ of the learning results so AR-based projects were limited to additional experiences sufficiently connected to the learning obtained using the experimental equipment. That is, generic information (i.e., videos or models about the operation of a pressure gauge, a pump, etc.), though interesting, were not selected here because they are more appropriate for interaction in less specific environments such as the classroom. As an example, it is not necessary to interact with pilot plant scale equipment to watch a video about pump operation principles. However, watching what happens inside a distillation column during operation (although it is possible to be shown also in a classroom) gives more credibility to the experience.

Moreover, if it is produced with the morphological matching of the video with the physical reality, this has an extra added value of credibility.

The analysis of the twelve proposals made it possible to select, according to the criteria established in Section 2.3, only four AR-based projects to be converted into prototypes:

(1) Batch distillation (*Experimentation in Chemical Engineering I* course);
(2) Continuous distillation (*Experimentation in Chemical Engineering I* course);
(3) Heat exchanger (*Heat Transfer* course);
(4) Non-ideal flow (*Chemical Reaction Engineering* course).

The proposal of viewing molecule models reacting in test tubes was ruled out as it was considered more suitable for a general chemistry laboratory, due to some development difficulties, such as the limited space and scale available. The difficulties do not allow good integration of real and virtual realities or the reusability in other experimental equipment. Moreover, great difficulty was expected in the development of own-made resources in this area.

It should also be noted that the characteristic with the least compliance was 'reusability'. This is an expected result given the technical specificity of each type of experimental equipment. In fact, the only two projects that did meet this criterion were related to unspecific equipment, such as pumps and pressure gauges, so they were discarded at first. Likewise, the AR-based experiences consisting of the mere appearance of pop-up dialogue that provide written information on the characteristics of the equipment were considered less interesting. These were considered to be redundant as the information could be obtained by classical learning procedures, such as the practical procedure checklist that was included in the gas-liquid absorber proposal.

Additionally, the proposals based on evaporation, catalytic reaction, or gas-liquid absorption with reaction equipment were also ruled out, since there was no possibility of developing own-made resources. The 'integration' of the numerous resources available on the internet was often inappropriate and of poor quality. Finally, it was considered that the experience of visualizing inside the reboiler of the open batch distillation equipment (*Basic Separation Operation* course) was redundant in favor of the batch distillation equipment (*Experimentation in Chemical Engineering I* course). The latter was preferred because it offered the possibility of incorporating more experiences with the same experimental equipment.

As a final reflection, it should be noted that the development of own-made resources often requires a greater degree of specialization in technical aspects (computing, 3D simulation, graphic design, etc.). Undoubtedly, the development of full-adapted high-quality resources requires the interdisciplinary co-work of experts in the development of digital resources and in Chemical Engineering teaching.

### *3.4. Prototypes Development*

The development of the four selected prototypes will be described and followed by an indication of the degree of achievement reached.

#### 3.4.1. Concentric Tube Heat Exchanger

As described in Table 4, the learning aim of this AR-based project was to provide contextual help in the form of a floating diagram, indicating the real direction of the flow of the hot water and the cold water streams. These streams change flow direction as a result of actuating the three-way valves installed in the experimental equipment, in order to operate in direct current or counter current. This management is conceptually complex for students who are unfamiliar with this type of valve. Moreover, part of the pipe routing is hidden in the physical disposition of the lines and the result of actuating on the valves is not so evident.

In this AR-based project, the markers for the launch of the digital resources were real images of the equipment with the valves positioned in different ways. So, the students would be informed in real-time of the type of contact model established (direct current or counter current) and, also, if the erroneous manipulation of the position of the valves could produce a risky situation, due to the closure of the hydraulic circuit. Intermittent tracks and paths would appear overlaid with the real image reporting the flow directions (see Figure 2).

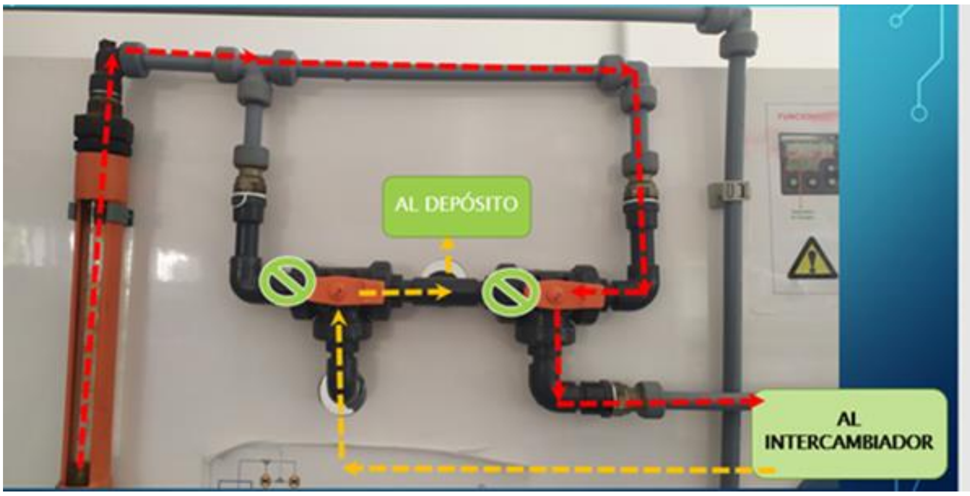


**Figure 2.** Capture from the concentric tubes heat exchanger AR-based Project. Dark green box text: "To the tank" in Spanish. Light green box text: "To the heat exchanger" in Spanish.

The digital resources that were overlaid on physical reality images were developed as GIF-type animations and they worked relatively well, but the markers, being real images, had an important dependence on the lighting conditions and the angle of focus of the device camera used. The appearance of glare or reflections is an added difficulty for the SDK platform or the app to recognize the image as a 'marker' and to start the running of the programmed routine. However, the 'integrability' of this AR-based project was excellent and the learning objective was considered fully achieved.

### 3.4.2. Continuous Stirred Tank Reactor

In this AR-based project, by focusing on the real reactor unit, an overlaid animated model of non-ideal flow would be reproduced. Since in this experiment, the monitoring of the residence time distribution curve is produced with a saline fluid (transparent) as the tracer, the students do not obtain any visual information about the poor mixing phenomenon taking place inside the reactor. However, with the AR resource implemented, the students can clearly visualize an animated model showing the poor mixing of a colored fluid.

The weakest aspect of this prototype was the 'integrability' of the digital resource with the physical reality. As can be seen in Figure 3, the trouble lay in the adaptation of a digital model (selected from the internet) with the shape and size of the real reactor unit used in laboratory practices. Meticulous technical work in the video treatment was necessary to eliminate the black background of the animation and to fit the shape of the real and virtual vessels.

Once the initial troubles were overcome, the experience was tested at the teacher level, revealing significant difficulties in recognizing the real image-based marker. The fact that the reactor was made of transparent glass, generated an image with too little useful information for the SDK or app recognition procedure. Moreover, the pattern of the visible images was distorted when light passed through the glass body, and changed with orientation, so the stability of the AR-based images was very poor. After numerous attempts to improve marker recognition, it was felt that this configuration was not appropriate. We concluded that the use of fixed images placed over key points on the experimental equipment brought more stability to the AR-based projects, despite a significant loss of the immersion feeling. Therefore, this proposal did not pass the students' test stage.

**Figure 3.** Real continuous stirred tank reactor (**left**), and raw digital flow model resource (**right**).

### 3.4.3. Batch Distiller

Applying the learning obtained from the previous AR-based prototypes, an AR-based project with three markers on the equipment was developed here. The aim of this experience was to provide information on the operation and position of the sampling valve of the pressurization balloon of the equipment in order to avoid accidental decompressions during the sampling procedure. This information would appear by means of a virtual floating label. In addition, it would appear as an explanatory video of the reflux splitter operation and what was happening inside the bottom reboiler, which is covered with opaque thermal insulation. Both the virtual valve label and the reboiler video were own-made, but the reflux splitter video was obtained from the internet. In Figure 4, a capture of the equipment and the used marker can be seen.

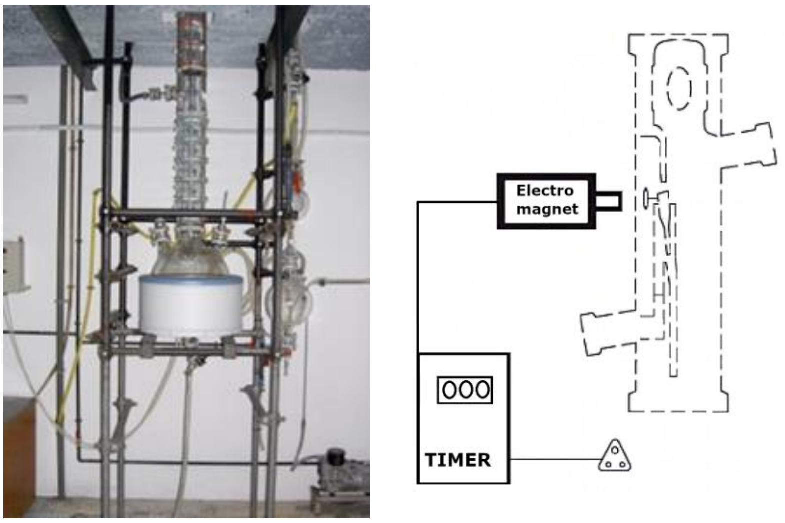


**Figure 4.** Capture of the downside of the pilot plant batch distiller (left), and AR marker for the reflux splitter device.

The experience was fully developed and put into use for testing by the teachers and collaborating students. It was concluded that the floating label did not integrate well with the equipment and it was a mere reminder of the indications in the practical procedure checklist. It was considered more interesting for the visualization of what was happening inside the reboiler. However, the students indicated that it would be more informative to visualize what was happening inside the column tray spaces (which were also hidden behind the thermal insulation). Finally, the experience with the reflux splitter was baffling because of the differences between the real and the virtual devices involved.

#### 3.4.4. Continuous Distiller

The continuous distiller prototype was developed with three different types of AR experiences, which were also implemented based on the previous one. These experiences were the following:

(1) An explanation of the flow model inside the heat exchanger used as a preheater. Here, a video from the internet was used. Despite the images being morphologically well adapted to the physical heat exchanger, no attempt was made to integrate both. Instead, the video was overlaid with a marker placed strategically next to the preheater.
(2) A video of the operation of a solenoid valve identical to the one installed in the reflux splitter. The marker was a fixed image, placed beside the real valve, to avoid the problems associated with real image recognition.
(3) A photo of the interior of the column operated as a 'virtual window' on which a recorded video of the interior of the column was reproduced (see Supplementary Material video S1). Here, a fixed image marker was placed at a strategic position of the thermal insulation of the distillation column (Figure 5). The physical marker was carefully placed so that the video matched in size and position with the 'see-through' effect of the insulator cover.

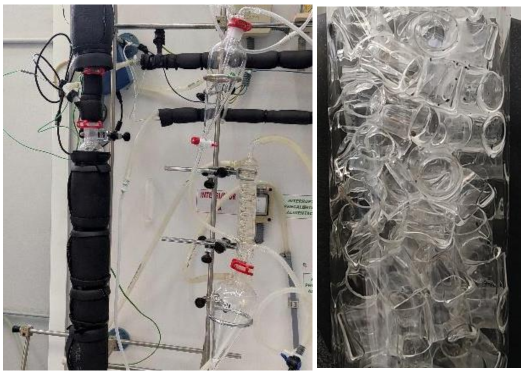

**Figure 5.** Bottom of the distillation column body (**left**), and still image of the distillation column inside (**right**).

Undoubtedly, the 'realistic' visualization of what is happening inside an opaque element is the AR experience that offers the best learning possibilities. The 'feeling' of going beyond physical reality is a very powerful tool for capturing attention, which is the promotor of discovery and knowledge. In the opinion of teachers, videos on fixed elements that are not part of the equipment are useful and a good educational complement, but their capacity to surprise is more limited.

As will be discussed in Sections 3.5 and 3.6, this prototype was tested and improved in several sessions with the feedback of the teachers' tests, and finally, it was chosen to be tested by the full group of the course students (44 students). The results of the surveys are presented in Section 3.6.1.

### *3.5. Implementation and Use of the selected AR-Based Teaching Tool*

The group of teachers involved in the development of the AR-based teaching tool previously selected, prior to making it available to the students, carried out on-site tests in the continuous distillation experimental equipment, located in the educational pilot plant. In these tests, the markers were placed in the most suitable locations, both, in operational terms (to launch the software routines properly when they are scanned by the device's camera) and in terms of safety during normal operation by the students with the experimental apparatus (see Figure 6). To decide these suitable locations, tests were carried out with different locations of the markers, with various devices and different capture angles and lights, selecting a final setup that allowed the correct development of the AR-based teaching tool (Figure 7 and see Supplementary Material Video S2).

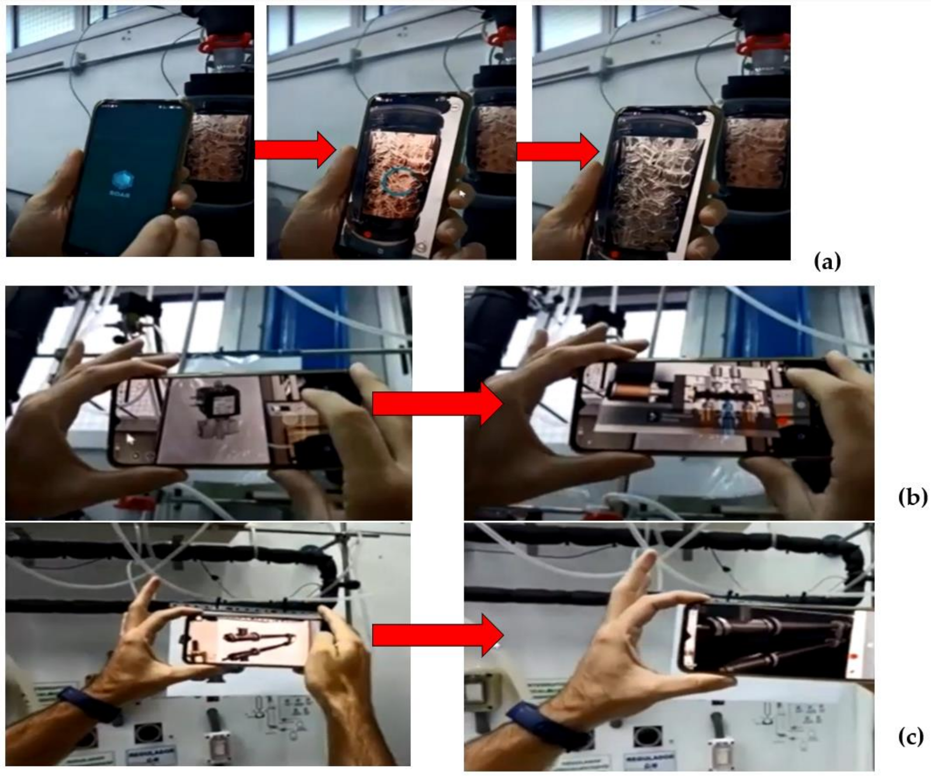

**Figure 6.** Different moments during the implementation and launch of the AR-based teaching tool. (**a**) Inner flow into the column; (**b**) Operation of the reflux valve; (**c**) Flow into the heat exchanger.

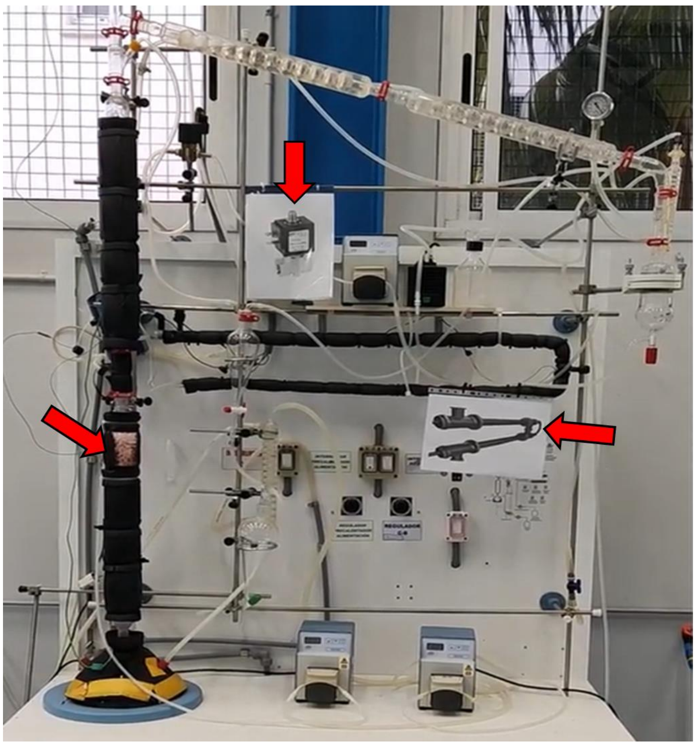

**Figure 7.** Continuous Distillation experimental equipment with the three markers created.

### 3.6. Assessment of the AR-Based Teaching Tool

To assess the AR-based teaching tool developed and implemented during the pilot plant sessions, post-surveys were carried out by the participants in this study. Thus, in order to know the impact and usefulness of the tool developed, the following subsections show and discuss the main results of the post-surveys carried out on students and teachers.

#### 3.6.1. Students

The assessment of the AR-based teaching tools, in terms of usefulness in learning, handling, and quality of the resources, was carried out through the opinion of the students involved in the project by means of post-surveys. Thus, in the first part of the questionnaire, the students had to rate through a ten point Likert-scale, a list of statements related to the usefulness and handling of the tool, during the sessions in the pilot plant (Figure 8).

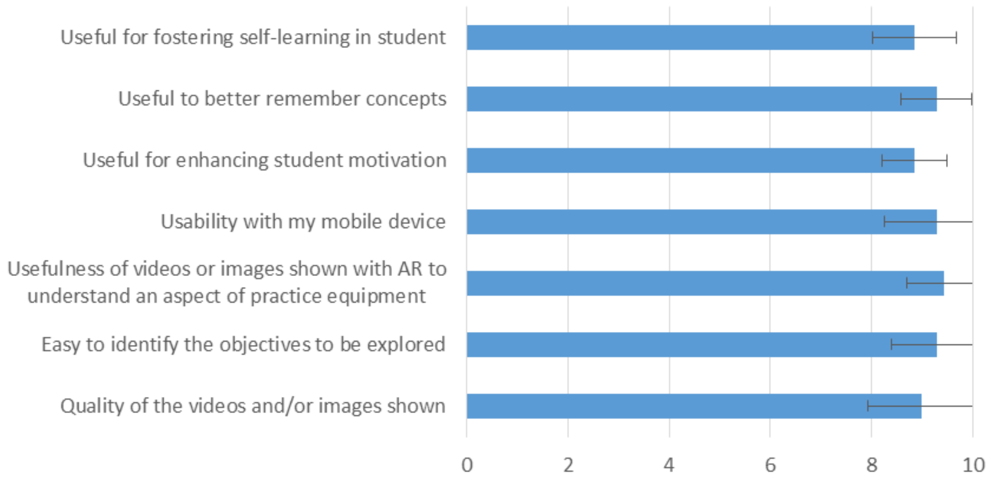


**Figure 8.** Average of responses of students about answers with ten point Likert-scale. Error bars show 95% confidence interval.

Although the control survey is not available (sessions of a group of students without access to the AR-based tool), it could be affirmed that the tool is very useful, due to the high average rating achieved (around 9). Specifically, the first question ('usefulness for promoting self-learning in student') obtained an average value of 8.8. The same average result was obtained when asked about the usefulness of enhancing student motivation. Even higher was the rating for 'remembering concepts previously seen in theoretical lectures' (9.2). The highest average rating (9.4) was obtained in the question about the 'usefulness of the resources shown to understand some element of the experimental equipment'. An average value higher than 9 was reached in the questions about the 'ease of use of the app with the mobile device and the location of the targets'. Finally, the 'quality of the displayed resources' was rated with an average score of 9.

In the same survey, students were asked to show their degree of agreement to a series of statements related to the perception of the AR-based teaching tool and its implementation (Figure 9), using a five point Likert-scale (strongly disagree to strongly agree). In all the cases, they strongly agreed that the tool is very useful as a support tool and they were unanimous in agreement with the idea of implementing more tools of this type in their practical sessions. In addition, 100% of the students disagreed, on a greater or lesser level, with the statement that 'the use of this type of tool is a curiosity but it is not useful for anything else'.

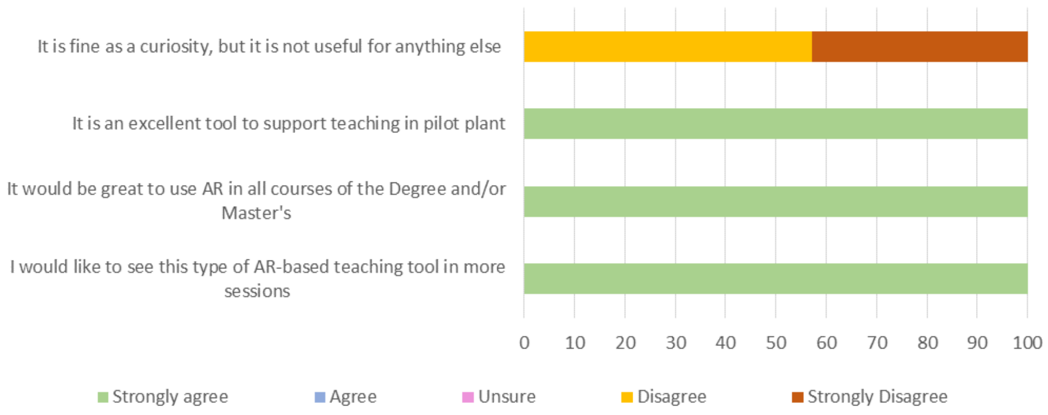


**Figure 9.** Average of responses of students about answers with five point Likert-scale.

As far as could be seen in the literature, there are few studies published to compare these results. Thus, the results obtained in terms of usefulness coincide with those observed by Low et al. [25], who show that 82% of the participants found the classes where AR-based resources were used useful, as it helped them in the retention of fundamental knowledge to later solve complex problems. Moreover, a high percentage of participants (92%), as in the present study, were in favor of including more AR-based resources as an additional resource to the existing learning materials in the experimental sessions.

In addition, looking at studies that have developed and implemented AR-based teaching tool experiences in other scientific fields such as Chemistry or Biochemistry, in which the use of AR-based tools as teaching material is more widely used, the results obtained are similar. As in this study, in all cases, the students positively rated the AR-based tools developed as an element to help them during the sessions [46–49].

### 3.6.2. Teachers

The opinions collected through the post-survey, from the 14 teachers participating in this study, are summarized in Figures 10 and 11. Those teachers included different academic ranks (professors, full professors, assistant professors, substitute professors, lecturers, senior lecturers, etc.), with teaching experience ranging from five to more than thirty years of educational career. Consequently, in the results obtained from the surveys, it should be expected that their assessment might be more severe than that of the students, due to their deeper knowledge of the experimental equipment and the learning process. However, as shown in Figure 10, the overall perception was positive, and 100% of the teachers gave an average response above 7.5. This rating can be considered very positive, indicating the usefulness of the AR-based tools as an element of pedagogical support, despite these AR-based tools being the first ones generated by this group of teachers.

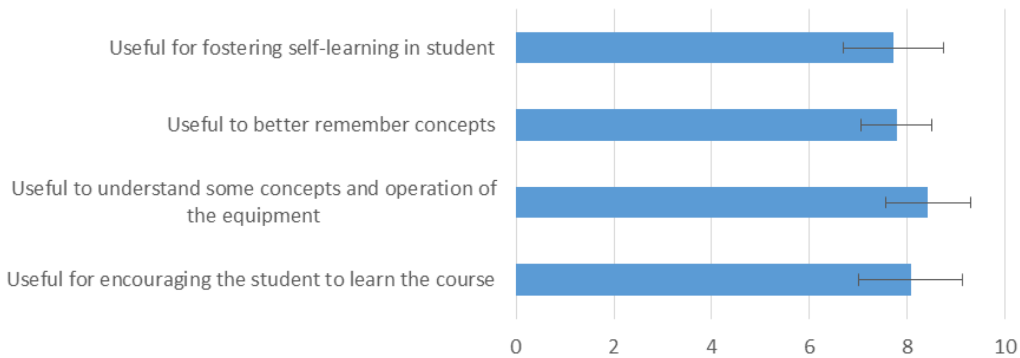


**Figure 10.** Average of responses of teachers about answers with ten point Likert-scale. Error bars show 95% confidence interval.

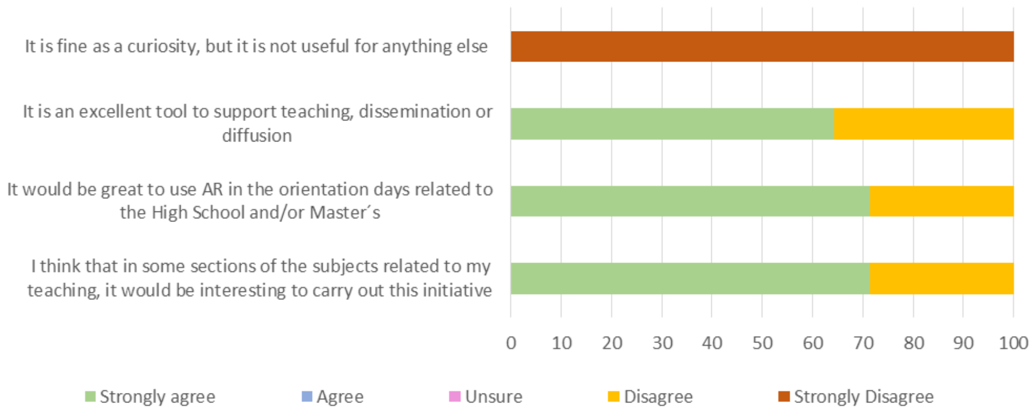


**Figure 11.** Average of responses of teachers about answers with five point Likert-scale.

Particularly, the response that obtained the highest score was the one about 'the assistance to students in understanding concepts or how equipment operates', with an average rating of 8.4. This perception coincides with that detected by Cortés Rodríguez et al. [46], where 82% of the teachers, involved in the development of a website with AR apps in Chemistry and Structural Biology, perceived that the use of that web helped students to better understand the contents studied in class.

Figure 11 shows the level of agreement with statements related to the usefulness of AR-based tools as teaching resources for teachers. Thus, the assessment was mostly positive, with more than 60% totally agreeing with that idea. It is worth noting that the response was unanimous in the total disagreement with the statement: 'AR resources are good as a curiosity but are not useful for anything else'.

It should also be noted that, in addition to the information collected through the surveys, the experiences and difficulties encountered by the teachers during the development of these AR-based teaching tools were collected through their comments in the management meetings of the project. Among these comments, it is worth highlighting that it is necessary to search for better resources and SDK in order to create good AR experiences. Another important comment is that it is difficult to generate own-made material, thus other available resources had to be used in most cases. The use of those existing resources did not always fit the requirements, which in many cases invalidated their further development. This limitation might be reduced with the support of a specialist from the other necessary fields [50]. Finally, another comment was related to the fact that teachers had to familiarize themselves with the use of the SDK by themselves, which also meant that additional time had to be spent on training. This type of training could be provided by specific teacher training programs, as has been previously identified by other studies [50,51]. All these encountered difficulties involved a significant amount of time above the usual teaching work [46].

## 4. Conclusions

The present study proposed the incorporation of AR-based tools into an educational pilot plant of Chemical Engineering. Considering the results obtained, the following could be concluded:

(1) Although a high quantity of audio-visual material related to Chemical Engineering education was initially found and stored on the internet, it was only on some occasions that this material was incorporated into the prototypes proposed by the teachers. The main reason was the difficulty to fit them completely into the projects, with the quality and specificity required. Hence, it is recommended to develop own-made audio-visual resources with the desired information and quality from the beginning.

(2) The creation of own-made resources that were fully adapted and of high quality, required a greater degree of specialization in technical aspects (computing, 3D simulation, graphic design, etc.). Thus, it is a good idea to design interdisciplinary work plans, in collaboration with experts in the creation of digital resources.

(3) The selection of the AR-based prototypes in order to be later fully developed, as an AR-based educational tool, should be driven by some specific criteria, such as the equipment scale, the accessibility to the images, the availability of audio-visual resources, the customizability of the products, the reusability of the tools, the specificity of the information and the integrability of all the elements involved.
(4) The AR-based teaching tools should include as many as possible AR experiences and provide information that is not redundant to that supplied in other ways (classroom sessions or practical procedure checklist).
(5) The results of the post-surveys suggest that students and teachers found AR experiences to be a very useful learning tool, highlighting the ability to help in the understanding of different elements of the experimental equipment.

The study could be a solid basis for the development of further AR-based educational tools in the pilot plant of Chemical Engineering. Nevertheless, the results obtained here cannot be generalized, because they are limited to students of a single project. Hence, further studies should be carried out to validate these conclusions in other courses and disciplines in the Chemical Engineering area. In addition, this study has opened up the following future possible lines of research:

- Implementation of methodological tools that make it possible to quantify the effectiveness of improving the degree of learning with the incorporation of AR resources in relation to a control group of students.
- Comparison of the efficiency of the above results with similar studies in other related fields in engineering (mechanical, electronic, electrical, informatical, etc.), including areas with industrial applications (rail, aviation, medicine, food, nuclear, etc.).

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci13010084/s1, Video S1: video of the interior of the column in Continuous distiller; Video S2: Augmented Reality Applied on Distillation Equipment (Demo video).

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