

A MODULAR APPROACH TO INTEGRATING BIOFUELS EDUCATION INTO ChE CURRICULUM

Part I – Learning Materials

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It has been argued that the advanced biofuels industry will have significant impact on U.S. economic recovery and its transition to a sustainable green economy. The U.S. National Academies have identified renewable energy as a national scientific strategy aimed at replacing the oil-based refinery and transitioning to a green economy.^[1] In addition, a study by the Biotechnology Industry Organization (BIO) showed that advanced biofuels industries will have significant impact on job creation and economic output in the near future, as shown in Figures 1.^[2]

Therefore, there is a pressing and immediate national need for skilled engineers and competent researchers in the biofuels field. This need also presents an exciting yet challenging opportunity for engineering educators to expand their mission to address biofuel production, and to contribute to this coming wave of change in the biofuels industry.^[3]

To address the educational need for the emerging biofuel industry, many universities have introduced biofuel or renewable energy education by offering courses and introducing programs in the past a few years.^[4-11] Table 1 lists some examples of such education efforts.

As illustrated in Table 1, although many biofuels education programs have emerged, most of them target a general non-engineering audience (such as agricultural or environmental majors, professionals in management, or the general public). As a result, these efforts usually cover non-engineering aspects such as national policies, environmental impact, economic analysis, and terminologies. In other words, they do not provide the technical education that is required to train technically advanced engineers and researchers.

On the other hand, there are many specialized research centers on biofuels technologies that have been established in the past few years, especially in the chemical engineering field. Several examples of such research centers are listed in Table 2.

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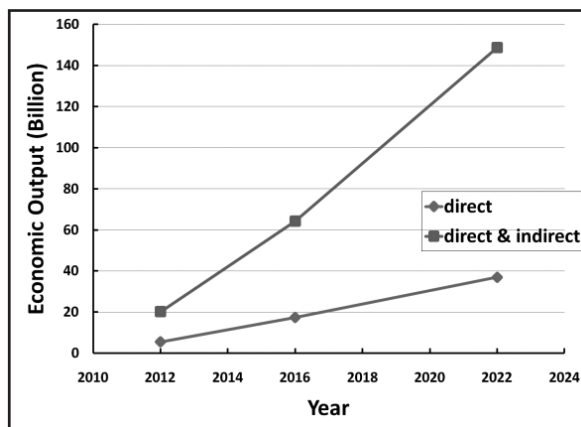
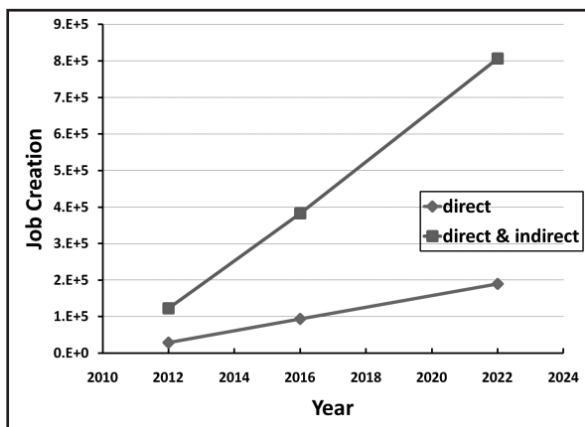
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Figures 1. Impact of advanced biofuels industries on (a, far left) job creation and (b, near left) economic output. (Adapted from Reference 2.)

TABLE 1

A short list of biofuels education programs

Program name	Institution / Department	Offering type
MBA and Certificate in Sustainable Business	Bainbridge Graduate Institute	MBA/Certificate in Sustainable Business;
Florida Center for Renewable Chemicals and Fuels	University of Florida / Institute of Food and Agriculture Sciences	Graduate Research Fellowships
The Center for Advanced BioEnergy Research	UIUC / College of Agricultural, Consumer and Environmental Sciences	Master of Science degree in bioenergy
Alternative Energy Technology: Biofuel	Central Carolina Community College	Associate/Certificate in biofuel technology
Sustainable Energy Initiative (SEI)	Oregon State University / Chemical Engineering; Crop and Soil Science;	Pilot projects for general public and high school students
Biofuel Production Operations Certificate Program	California State University - East Bay / Continuing Education	6-month Certificate in biofuel production operations
Alternative Energy Programs	Crowder College / Environmental Sciences	Associate of Arts degree
Biodiesel Fuel Education Program	University of Idaho / Biological & Agricultural Engineering	Online short course for general public
New York Center for Liquid Biofuel	Morrisville State College / School of Agriculture and Natural Resources	Create jobs in the agriculture sector

TABLE 2

A short list of large research centers funded by DOE, USDA, and other agencies

Center/Laboratory name	Institution / Department
Engines & Energy Conversion Laboratory (EECL)	Colorado State Univ. / Dept of Mechanical Engineering
Center for BioEnergy Research and Dev. (CBERD)	South Dakota School of Mines and Tech. (lead), multi-univ. / multidiscip.
Biomass Energy Center	Pennsylvania State Univ. / multidiscip. (includes chem. engineering)
Office of Biobased Technologies (OBT)	Michigan State Univ. / multidiscip. (includes chem. engineering)
The Institute for Massachusetts Biofuels Research	Univ. of Massachusetts, Amherst / multidiscip. (includes chem. engineering)
Biofuels Research Laboratory (BRL)	Cornell Univ. / Depart. of Bio. & Environmental Engineering
Center for Direct Catalytic Conversion of Biomass to Biofuel	Purdue Univ. / multidiscip. (includes chemical engineering)
Catalysis Center for Energy Innovation (CCEI)	Univ. of Delaware (lead), multi-univ. / multidiscip. (led by chemical. engineering)
Combustion Energy Frontier Research Center	Princeton Univ. (lead), multi-univ. / multidiscip. (includes chemical engineering)
Bioenergy Systems Research Initiative (BSRI)	Georgia Tech / multidiscip. (includes chemical engineering)
Bioenergy Research Group (BERG)	Univ. of California, Davis / multidiscip. (includes chemical engineering)

These research centers mainly focus on advanced research and graduate/post-graduate education in engineering.^[7,12-14] The research results generated from these centers, other research groups, and individual researchers are usually published in scientific journals, which involve a high level of technical knowledge and complexities that are intended for highly technical audiences such as other research scientists and development engineers. Although some universities have been offering biofuels-related courses in engineering, we believe the gap between advanced biofuels research and undergraduate biofuels education in engineering is still significant and worth addressing.

APPROACH/METHOD

Among different engineering majors, chemical engineering is in a unique position to address this educational need. This is because most processes associated with biofuels are chemical or biochemical processes and all the underlying principles of biofuel processes, such as mass transfer, heat transfer, and reaction engineering, are the same as those of traditional chemical or petrochemical processes. The only differences are that, in biofuels processes, different unit operations are arranged in different ways, and different raw materials are processed in biofuels plants. These similarities indicate a much easier transition from a traditional chemical engineer to a biofuels engineer compared with students from other engineering disciplines. Of course, biofuels processes have their unique characteristics and challenges. In general, biofuel processes are more complex than the traditional chemical or petrochemical processes partially due to the complex raw materials (*e.g.*, lignocellulosic biomass, municipal wastes, etc.) and multiple reactions associated with the complex raw materials. This perhaps is one of the major reasons for the lack of comprehensive yet simple enough educational material on biofuels processes that can be easily adopted into chemical engineering curricula. Although there are some engineering textbooks^[15-20] published in the biofuels area, due to the challenges associated with adding new courses or changing curricula, they have not been widely adopted. Partially because of the lack of appropriate educational materials, existing undergraduate biofuels educational efforts are often too fragmented to achieve critical mass for a visible impact on students' understanding of biofuel technology when they graduate.

It is worth noting that over the years chemical engineering curricula have primarily focused on the traditional chemical and petrochemical industry. In other words, most examples, homework problems, exams, and design problems are developed based on the traditional chemical and petrochemical processes with some exceptions, *e.g.*, Reference 14. The fundamental principles and concepts that are involved in chemical processes (which are the same for biofuel processes) are introduced cumulatively through a modular approach, such as

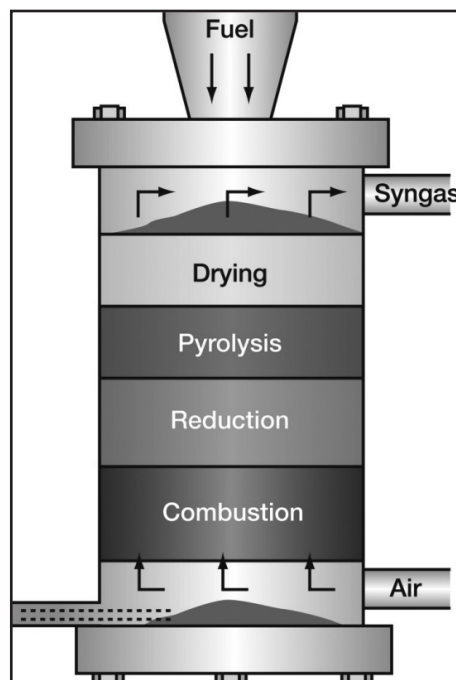


Figure 2. Different zones in an updraft gasifier (source: <<http://www.biomasa-elektika.com/>>).

mass transfer, heat transfer, material balance, reactor design, and process control. Based on this observation, we believe that an alternative approach (in contrast to a single biofuels course) of teaching chemical engineering students biofuels technology is to adopt a similar modular approach by creating comprehensive yet flexible and apprehensible biofuel learning modules that are compatible with the existing modular courses for easy integration or adoption.

Specifically, instead of developing a separate senior course that is devoted to biofuels processes, we propose to break down the biofuels processes into small pieces such as unit operations, and each piece can be further broken down and simplified to illustrate different chemical engineering principles or concepts. For example, a gasifier is one of the process units in a gasification process^[21]; it can be further simplified to illustrate mass balance or energy balance. Or it can be further broken down to different zones as shown in Figure 2 (*e.g.*, drying, pyrolysis, reduction, and combustion) to illustrate different heat effects, such as sensible heat, latent heat, and heat of reaction. In this way, lower-level students will not be overwhelmed by the complexity of a biofuels process when they do not yet have all the background knowledge to comprehend it as a whole; meanwhile, higher-level students will feel much more comfortable in designing a complex biofuels plant because they have seen all the pieces in their lower-level courses, maybe even multiple times. We hope this modular approach will result in a better student-learning outcome than a “single-course” approach, or at least it can be used to supplement and enhance the single-course approach.

Based on the modular approach, we have been developing a series of classroom learning modules that can be easily

TABLE 3 Key components of a classroom module
• Associated sections in selected textbooks
• Module learning objectives
• Web module links
• Process background and problem
• References
• Solutions (for instructors)

integrated into existing chemical engineering curricula. The key components of each module are listed in Table 3. The modular and extensible nature of the learning material will enable instructors to easily select, share, expand, and modify the materials to fit students with various learning capabilities and career goals.

Due to the complex nature of biofuels processes and students' limited exposure to biofuels technology, most students would feel incompetent in dealing with problems related to biofuels. To help students overcome this barrier, we have also been creating a series of web modules to accompany the classroom modules by exploiting two instructional strategies: computer-assisted instruction and visual learning. Computer-assisted instruction is an innovative instructional strategy that has been receiving increasing attention in engineering education.^[22] It has been shown that computer-assisted instruction provides students with rapid inquiry-based learning experiences, allowing students to proceed at their own pace and within their own schedule.^[23-25] Visual learning—the use of graphics, images, and animations to enable and enhance learning—has been shown to be effective in exploiting students' visual senses to engage students in active learning, support traditional lessons, and make their learning experience stronger and deeper.^[26-32] This methodology also has the potential to increase the number of students in science, technology, engineering, and math (STEM) fields, especially for women and minority students.^[30]

The key components of the web modules include: glossary, process introduction, process flow diagram, captured and animated process video clips, visual encyclopedia of equipment, reference shelf, and solved problems. While classroom modules focus on the fundamental aspects of biofuels technology that are more suited to the current undergraduate chemical engineering curriculum, the online web modules will provide more background knowledge and other resources to assist students with understanding classroom modules. In this way, students will not only be exposed to biofuels technology, but also get fresh stimuli in learning chemical engineering principles. Besides assisting students with classroom modules, another intended goal of the web modules is to use recently emerged effective teaching strategies combined with the “hot” topic of biofuels to stimulate students' interest in learning traditional chemical engineering principles.

RESULTS

Classroom modules

We have developed classroom modules for chemical engineering thermodynamics and chemical reaction engineering courses. Specifically, classroom modules have been created to cover the following four topics in chemical engineering thermodynamics that are compatible with Chapters 4, 6, 10, 11, and 12 of the commonly used textbook by Smith, Van Ness, and Abbott.^[33]

- *Heat effects in biofuels processes*
- *Thermodynamic properties of biofuels*
- *Vapor/liquid equilibrium in biofuels processes*
- *Biofuels solution thermodynamics*

In addition, classroom modules have been developed to cover the following topics of chemical reaction engineering that are compatible with Chapters 1-5 and 8 of the textbook by Fogler.^[34]

- *Design equations for batch and continuous gasifiers*
- *Rate laws and stoichiometry for various biofuels reactions*
- *Design of CSTRs and packed bed reactors (PBRs) for biofuels processes*
- *Multiple reactions in biofuels processes*

One classroom module is provided in Figures 3 (on two following pages) as an illustrative example.

As can be seen from Figures 3, each classroom module is linked to one chapter or some sections of the most commonly used textbooks, as indicated in the “Associated Sections in Selected Textbooks” section of each module. In this way, there are no textbook or even any course syllabus changes or additions needed, making adoption extremely easy—the instructor can straightforwardly replace or supplement some of the textbook examples and homework problems with the examples and problems provided by the classroom module. As shown in the dashed-line frame in Figures 3, the problem part is essentially the same as a typical textbook example or homework problem without the involvement of any biofuels process. In addition, the “Web Module Links” point students to relevant web modules to promote active learning and student engagement. Finally, for some topics, one or more comprehensive, open-ended design problems will be provided. One example design problem is provided in the Appendix.

Web modules

For the web modules, we have been developing a glossary, collections of commonly used equipment, different biofuel processes, animated video clips, and a reference list.

Specifically, we have developed a comprehensive glossary of frequently used acronyms and definitions of various specialized

terms used in the biofuels industry with hundreds of entries, which provides explanation to common terminologies in biofuel technology. Chemistry and chemical engineering details are included to make them more technical and job-oriented. At the time this paper was being written, we have included more than 500 terms. This glossary serves as an essential resource for students with little or no biofuels background.

We also have developed a collection of common equipment used in biofuel processes, namely the Visual Encyclopedia of Equipment, which includes a wealth of photographs, drawings, videos, and descriptions of different equipment used in different biofuel processes, such as gasifiers, pyrolyzers, and reformers. This resource also serves as a tool to enhance students' biofuels background. So far we have developed more than 40 equipment modules. Due to limited space, we can only provide an abridged screenshot of an equipment module, as shown in Figure 4 (page 104).

Besides individual equipment, we have developed web modules for the different pathways employed by different biofuel processes, including gasification, fermentation, pyrolysis, combustion, and liquefaction. For each pathway, we classify the process based on technology and feedstock. For example, for gasification, we have developed seven web modules based on different technologies and nine based on different feedstocks (the left figure in Figures 5, page 104). For fermentation, we have developed six modules based on technology and seven based on feedstock (Figure 5, bottom). Each module includes a technical introduction of the process, the process flow diagram, equipment or reactors, related videos and glossary terms, and references. While the classroom modules focus on one element of a process to develop fundamental understanding of specific topics individually, the web modules are process-oriented and present a range of concepts and fundamentals in the context of the larger biofuels process under investigation. In other words, they provide students a complete or holistic description of a process that involves different fundamental principles and concepts, such as mass transfer, heat transfer, and phase equilibria.

In addition, to enhance students' visual learning by illustrating the process material/energy flow and reactions in action, we have also developed animated process video clips for many biofuels processes including combustion, pyrolysis, liquefaction, different types of gasifiers, Fischer-Tropsch reactors, and others.

Application of modified Raoult's law in a vacuum fermentation process

【Associated Sections in Selected Textbooks】

- Introduction to Chemical Engineering Thermodynamics [1] Sec. 10.5

【Module Learning Objectives】

- VLE calculation using modified Raoult's law.
- Vacuum fermentation

【Web Module Links】

- Vacuum fermentation: <http://biofuelsacademy.org/web-modules/process/fermentation/vacuum-fermentation/>

【Process Background and Problem】

Since typical fermentation broth contains low levels of ethanol, much of the energy consumption for commercial ethanol production is for distillation. Significant energy savings can thus be achieved if ethanol-rich fermentation broth is used. However, the growth and production ability of cells are inhibited by high ethanol and/or sugar concentration [2]. To prevent product inhibition, ethanol product must be removed from the fermentation broth as soon as it is formed. Simultaneous removal of ethanol stimulates the growth of yeast cells; thus, more sugars can be fermented and higher ethanol productivity was achieved as a result [2]. One way to achieve this is through vacuum fermentation. One particular design is shown in the following figure [3].

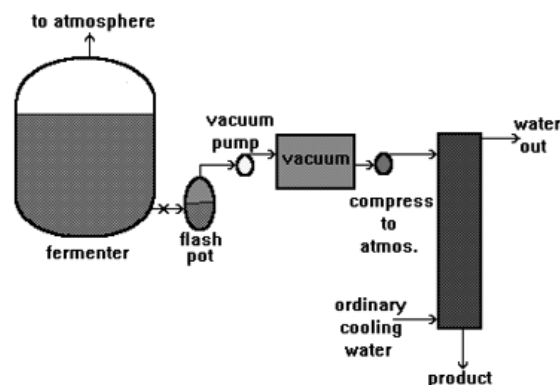


Figure 1. Schematic diagram of vacuum fermentation [3]

Figures 3 (above and facing). Example classroom module. Content in the dashed-line frame (i.e., the problem part) resembles a typical textbook example or homework problem without the involvement of any biofuels process.

The animated videos were created based on process flow diagrams, equipment illustrations, and cutaway drawings. Video clips provide a vivid description of how a process operates, including, for example, the flow of material streams, details of the reactions, and energy exchanges. Compared to verbal descriptions, these videos provide students with a more intuitive and dynamic view of the process, which could significantly improve students' understanding of a process. All videos are accompanied by narrations and are shared on YouTube. Collectively, the videos have been viewed more than 14,500 times in the past year. In addition, we have also included more than two dozen biofuels-related videos developed by other organizations.

The fermentation broth is circulated through the flash pot for vaporization of the ethanol. The vacuum is adjusted to the vapor pressure of the alcohol-water solution at the fermentation temperature (30 to 40 °C).

Assume the ethanol-water solution in the flash pot reaches equilibrium and the modified Raoult's law applies. The following equations provide a reasonable correlation for the activity coefficients:

$$\ln \gamma_1 = Ax_2^2 \quad \ln \gamma_2 = Ax_1^2 \quad \text{where } A = 2.65 - 0.00575T(K)$$

- If the fermentation broth at 35°C contains 0.1 mole fraction of ethanol, what would be the pressure in the flash pot and what is the mole fraction of ethanol in the vapor phase?
- If we want to achieve 0.5 mole fraction of ethanol in vapor phase at 35°C, what would be the ethanol mole fraction from the fermentation broth? And what would be the pressure in the flash pot?
- If the fermentation broth contains 0.1 mole fraction of ethanol and we want to maintain the vapor pressure in the flash pot at 5 kPa, what would be the operation temperature of the flash pot? And what would be the mole fraction of ethanol in the vapor phase?
- If we want to maintain the vapor pressure in the flash pot at 5 kPa, at the same time achieve 0.4 mole fraction of ethanol in the vapor phase, what would be the ethanol mole fraction from the fermentation broth? What would be the operation temperature of the flash pot?
- Show whether or not the system exhibits an azeotrope at 25°C. If there is an azeotrope, what are the azeotropic pressure and the azeotropic compositions for $t=25^\circ\text{C}$?

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Figures 3. continued.

Finally, we have compiled a comprehensive reference list. In it, students can find additional information for further study. The reference list includes hundreds of books, journal articles, and website links related to biofuels technology.

All the classroom and web modules are hosted on the website <www.BiofuelsAcademy.org>, which is the project website dedicated to chemical engineering undergraduate biofuels education.

CONCLUSIONS

This work was motivated by the potential need for a technologically advanced workforce and innovative researchers in the biofuel field. To address this need, we first identified the gap between advanced biofuels research and undergraduate biofuels education in engineering. We then introduced a modular approach to bridge this gap by creating educational materials that systematically integrate biofuels education into chemical engineering curriculum. Specifically, we have created a set of classroom modules by simplifying and decomposing complex biofuel processes. Each classroom module focuses on one chemical engineering theory or principle, e.g., one topic or section of a typical textbook such as sensible heat or heat of reaction, making it easy for wide adoption. To

accommodate different learning styles and enhance students' active engagement through computer-assisted instruction and visual learning, we have also created a series of web modules to accompany the classroom modules. We expect that the unique combination of classroom modules with web modules will effectively enhance students' understanding of chemical engineering principles, as well as significantly increase students' exposure to biofuels technology.

We hope that there is a wide adoption of our learning materials among chemical engineering educators because our approach can effectively address the following three major obstacles of introducing biofuels education into chemical engineering curricula: (1) there is a lack of learning materials that are appropriate for undergraduates; (2) not all academic programs will be able to accommodate additional course(s) with all other programmatic requirements currently in place; and (3) any changes to the curriculum that require significant effort from faculty or staff would be difficult to sell and adopted widely.

In the proposed framework, the classroom modules serve as the supplementary materials to existing chemical engineering textbooks. In other words, our primary goal is still for students to understand and apply chemical engineering principles. Introducing biofuels education is the secondary goal, which exposes students to contemporary issues and industrial/national needs. Therefore, the basic concepts and fundamental principles from classic textbooks are still represented and are taught in the same way as in a traditional chemical engineering class. The examples and homework problems provided in the developed biofuel modules can be used to replace/supplement some of the textbook examples and homework problems.

The advantages of this modular approach that make it easy for adoption are summarized in Table 4 (page 105) from both instructors' and students' points of view.

FUTURE WORK

We have integrated the developed biofuels learning modules into two chemical engineering core courses: thermodynamics and chemical reaction engineering. We are

Figure 4, right. An abridged screenshot of an equipment web module. Full module can be found at: (<<http://biofuelsacademy.org/web-modules/equipment/bin-and-storage-unit/hammermill-surge-bin/>>)

currently evaluating student learning outcomes and will report the results in a separate paper. Once the learning modules are refined, we will explore several avenues for wide dissemination, including but not limited to periodic updates and improvements to our website and content, direct contact with professors at other institutions and workshops, and presentations/posters at conferences.

ACKNOWLEDGMENT

Financial support from the National Science Foundation under Grant No. 1044300 and the U.S. Department of Agriculture through the Southeast Partnership for Integrated Biomass Supply System (IBSS) are greatly appreciated.

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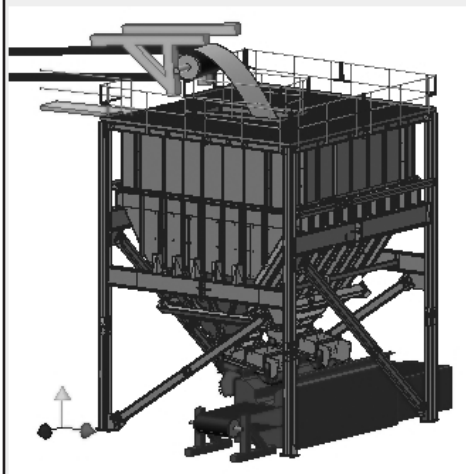
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Hammermill Surge Bin

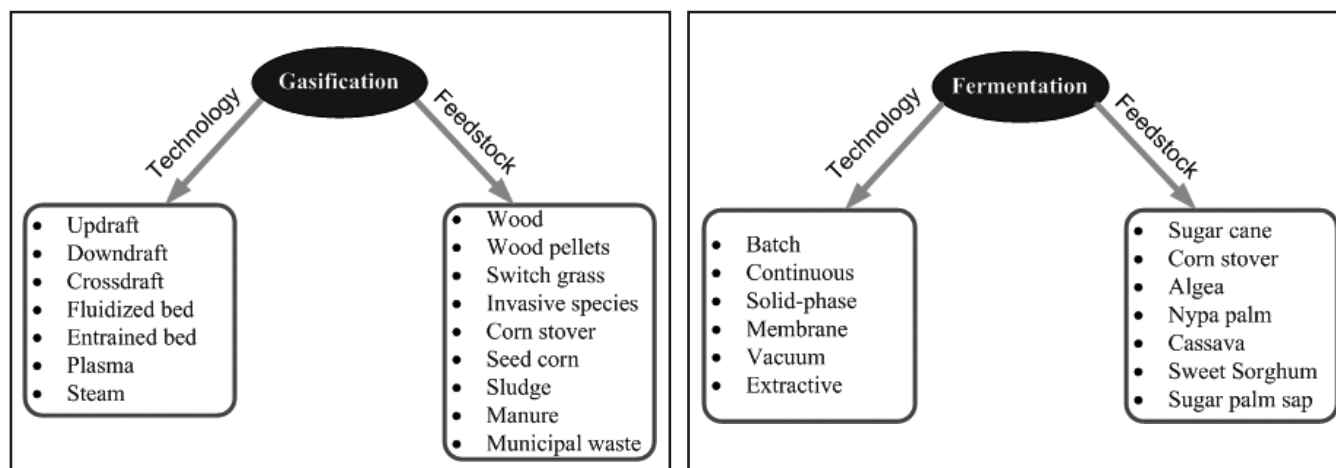
• Introduction

The primary function of a hammermill surge bin in a biofuel process is to provide a controlled constant feed from a hammermill to a secondary source without taking on the wear & tear of operating a belt feeder associated with the larger sized biomass material, and yet maintain the required mobility. The surge bin is usually mounted on legs to elevate the bin to a height which permits a truck to be driven underneath the surge bin. A gate in the bottom of the surge bin is then opened and the material falls out of the bin into the truck below. Surge bins are often mounted on a trailer for easy mobility from one site to the next.

• Figures



(source: http://www.diccionario-tecnico.com/definicao-significado/surge_bin_71241.html)



Figures 5. Process web modules based on technology and feedstock. Two examples: gasification (left) and fermentation (right).

TABLE 4
Advantages of the proposed modular framework for biofuels education

Features	Benefits to instructors	Benefits to students
Compatibility	No textbook/syllabus change or addition	Reduces psychological barrier
Modularity	Independent modules/problems enable free choice of use	Learning of one module will not negatively affect their learning of others
Flexibility	Easy to modify/add example/homework	Allows students to have input into the types of problems they would like to see
Comprehensive problem collection	Ample examples/homework to choose from	Ample examples to learn and ample homework to exercise on
Solution availability	Solutions to examples/homework are provided– no extra burden for instructors	Example solutions help develop strong problem solving strategies and skills
Web modules	Reduce classroom time spent on modules and minimize disruption to existing curriculum because great details are provided in the corresponding web modules	Provide additional resource and assistance that enhance student learning; encourage self-learning; address different learning styles

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APPENDIX

Rotary dryer design

A rotary dryer consists of a revolving cylindrical shell, horizontal or slightly inclined toward the outlet. Wet feed enters one end of the cylinder; dry material discharges from the other. As the shell rotates, internal flights lift the solids and shower them down through the interior of the shell. Rotary dryers are heated by direct contact of air or gas with the solids, by hot gasses passing through an external jacket on the shell, or by steam condensing in a set of longitudinal tubes mounted on the inner surface of the shell. The last of these types is called a steam-tube rotary dryer.^[A1-A3]

A typical countercurrent direct-contact air-heated dryer is shown in Figure A1. A rotating shell A made of sheet steel

is supported on two sets of rollers B and driven by a gear and pinion C. At the upper end is a hood D, which connects through fan E to a stack, and a spout F, which brings in wet material from the feed hopper. Flights G, which lift the material being dried and shower it down through the current of hot air, are welded inside the shell. At the lower end the dried product discharges into a screw conveyor H. The air is moved through the dryer by a fan, which may, if needed, discharge into the air heater so that the whole system is under a positive pressure. Alternatively, the fan may be placed in the stack as shown, so that it draws the air through the dryer and keeps the system under a slight vacuum. This is desirable when the material tends to dust.

In a biomass gasification plant,^[A4] it is required to process wet biomass containing 50 wt % moisture at a rate of 60 kg/min. For the discharged dried biomass, the solids content must exceed 80 wt %. Hot air is available at 350 °C with a humidity of 0.01 kg/kg dry air, and the maximum mass flow rate of the air that can be provided is 20 kg/s. Design an air-heated rotary dryer that satisfies the above requirements. You can make the following assumptions: The heat capacity of the dry biomass is 1.7 kJ/(kg·K), the initial temperature of the wet biomass is between 15 °C and 30 °C, the temperature of the

dried biomass at the discharge is between 70 °C and 90 °C, the temperature of the moist air at the outlet is between 110 °C and 130 °C. The heat capacities of air and water can be found in handbooks or online. The enthalpies of the saturated and superheated steams can be found in the steam table.

Additional information about dryer design can be found in the “Reference Shelf” section of the web module. For example, “APV Dryer Handbook” provides a guide to dryer selection and the ways to improve thermal efficiency in a dryer. In addition, more dryer pictures and videos can be found in the “Visual Encyclopedia of Equipment” section of the web module and in “The Visual Encyclopedia of Chemical Engineering Equipment.”^[A3]

REFERENCE ON ROTARY DRYER

- A1. <http://internet.processmanual.com/ipmcontent/DR_4.htm>
- A2. <<http://biofuelsacademy.org/web-modules/equipment/dryer/rotary-drum-dryer/>>
- A3. Montgomery, S., “Teaching Tips: Beyond the Black Box—Helping Your Students Visualize How Chemical Engineering Equipment Works,” *Chem. Eng. Ed.*, **46**(1), inside front cover (2012)

REFERENCE ON GASIFICATION:

- A4. <<http://biofuelsacademy.org/web-modules/process/gasification/>> □

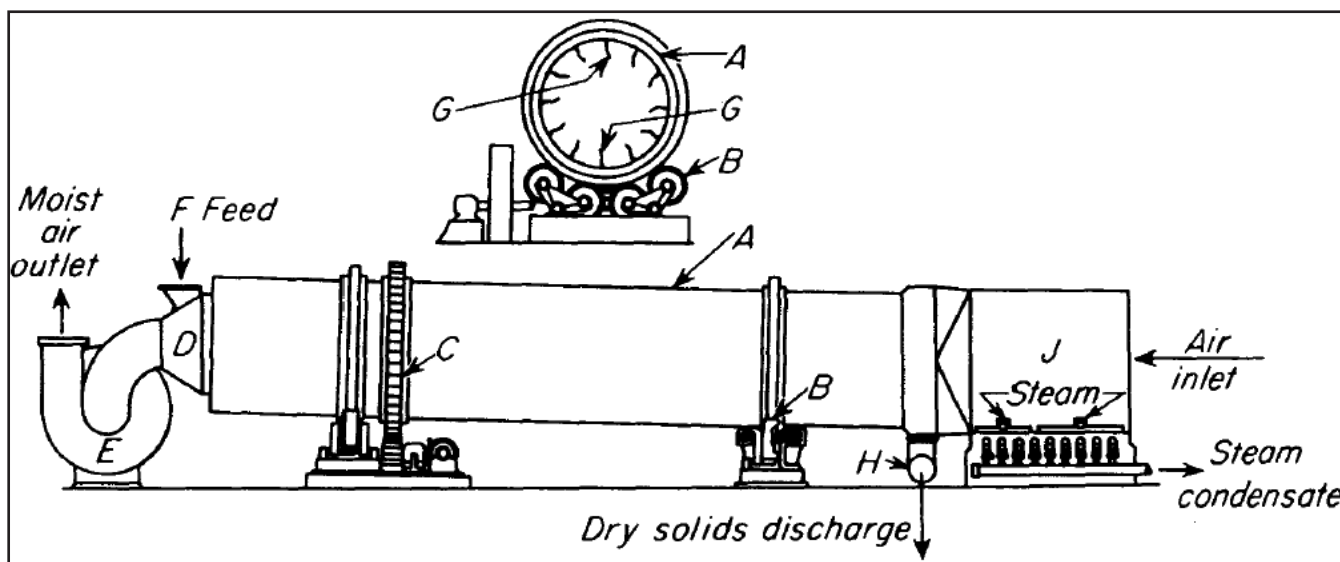


Figure A1. Countercurrent direct-contact air-heated rotary dryer: A, dryer shell; B, shell-supporting rolls; C, drive gear; D, air-discharge hood; E, discharge fan; F, feed chute; G, lifting flights; H, product discharge; J, air heater. (Image source: <<http://putrapratamadany.blogspot.com/2011/05/alat-bernama-rotary-dryer.html>>).