Second Year Annual Report: NSF/CRCD 9980325 Multiphase Transport Phenomena Curriculum Development

Performance Dates:	December 2001 through January 2002 (second year)
Award Dates:	November 17, 1999 to November 16, 2002 (one year no cost extension)
First Year NSF Award:	$250,000
Second Year NSF Award:	$250,000
NSF/REU Supplemental:	First Year, $10,000
NSF/REU Supplement:	Second Year, $35,625
MSU, UA, & UT Cash Match:	$125,000
MSU Cash Supplemental:	$16,000
Total Two-Year Project Cost:	$545,625 (NSF), $141,000 (MSF, UA, & UT)

1. Project Participants (Cumulative, December 1999 to present)

1.1 Principal and Co-Principal Investigators:

Name	Title	University/College	Department
Charles A. Petty	Professor	MSU/Engineering	Chemical & Materials Science
Mei Zhuang	Associate Professor	MSU/Engineering	Mechanical
George G. Chase	Professor	U. Akron/Engineering	Chemical
Ram S. Mohan	Associate Professor	U. Tulsa/Engineering	Mechanical

1.2 Faculty Associates

Name	Title	University/College	Department
Marilyn J. Amey	Associate Professor	MSU/Education	Higher, Adult, & Lifelong Education
André Bénard	Assistant Professor	MSU/Engineering	Mechanical
Krishnamurthy Jayaraman	Professor	MSU/Engineering	Chemical & Materials Science
Edward A. Evans	Assistant Professor	U. Akron/Engineering	Chemical
Thomas D. Radcliff	Assistant Professor	U. Akron/Engineering	Mechanical
Ovadia Shoham	Professor	U. Tulsa/Engineering	Petroleum
Keith D. Wisecarver	Associate Professor	U.Tulsa/Engineering	Chemical
Siamack A. Shirazi	Associate Professor	U.Tulsa/Engineering	Mechanical

1.3 Postdoctoral Associates

Name	University/College	Department	CRCD Participant	Industrial Case Study
Steven M. Parks	MSU/Engineering	Chemical	December 1999 to present	Krebs
Shiwei M. Shao	MSU/Engineering	Chemical	December 1999 to October 2000	Pharmacia

1.4 Other Technical Collaborators on the Project, Second Year

MSU Division of Engineering Computing Services	Frederick Hall
MSU Virtual University Technology Group	Randy Russell & Chanelle Embrey

1.5 Graduate Student Participants

Name	CRCD Advisor	CRCD Contribution		
		Academic Case Study	Industrial Case Study	CFD Mentor
Ferhat Erdal	S. Shirazi	2000	Chevron 2000	2000
Luis Gomez	R.Mohan & O. Shoham	2000	Krebs 2000 Chevron 2001	2000 & 2001
Judd Hark	M. Amey		Assessment	
Sang-Yoon Kang	K. Jayaraman	2000		
YoChan Kim	C. Petty		Pharmacia 2001	2001
Figen Lacin	M. Zhuang	2000	Trane 2000 Trane 2001	2000 & 2001
Hongmin Li	E. Evans	2000	Krebs 2000 Eastman 2001	2000 & 2001
Dilip Mandal	A. Bénard	2000	Trane 2001	2001
Chinh Nguyen	C. Petty	2000		2000
Brian Raber	G.Chase	2000	Eastman 2000 Eastman 2001	2000 & 2001
Michael Shafer	C. Petty		Trane 2000	
Dogan Seyyar	A. Bénard	2000		
Jin Wang	K. Wisecarver	2000	Eastman 2000	

1.6 Undergraduate Student Participants, First Year

Name	University	Faculty Advisor	Industrial Case Study
Florin R. Danca	MSU	K. Jayaraman	Chevron
Dina A. El-dein	MSU	Charles Petty	Trane
Joshua Herron	U. Akron	Edward Evans	Eastman
Seth Jentner	U. Akron	George Chase	Chevron
Nicholas F. Lynn	MSU	Mei Zhuang	Trane
Gregory A. McColley NSF/REU	MSU	K. Jayaraman	Eastman
Julie A. Richards	MSU	André Bénard	
Jose Severino	U. Tulsa	Ram Mohan	Chevron
Michael T. Skeggs NSF/REU	U. Akron	George Chase	Pharmacia
Andrew R. Yoder,	MSU	Charles Petty	Pharmacia

1.7 Undergraduate Student Participants, Second Year

Name	University	Faculty Advisors	Industrial Case Study
Kathryn Baker NSF/REU	MSU	Chase/Petty	Eastman
Dina A. El-dein NSF/REU	MSU	Zhuang/Petty	Trane
Christina Berger NSF/REU	MSU	Petty/Parks	Pharmacia
Troy Hendricks NSF/REU	MSU	Chase/Petty	Eastman
Steve Leibrandt NSF/REU	MSU	Zhuang/Petty	Chevron
Nicholas F. Lynn	MSU	Zhuang/Petty	Trane
Luwi Oluwole	MSU	Parks/Petty	Krebs
Carl Rose NSF/REU	MSU	Petty/Parks	Pharmacia
Jose Severino	U. Tulsa	Mohan/Ovadia	Chevron
Sara Vermillion NSF/REU	U. Akron	Chase/Edwards	Eastman
Floyd Hammond NSF/REU	U. Tulsa	Mohan/Ovadia	Chevron
William Wehbe	MSU	Parks/Benard	Krebs
Andrew Yoder,	MSU	Petty/Parks	Pharmacia

1.8 Industrial Mentors for the CFD Case Studies, Second Year

Company	NSF/CRCD Industrial Mentor	Project Title
Pharmacia	Mark Widman	Numerical Simulation of a Solid/Fluid Suspension in an Enclosed Tank
Trane	Ray Rite	Numerical Simulation of a Refrigerant in a Distribution Manifold
Eastman	Kevin Fonetnot	Numerical Simulation of a Bubble Column
ChevronTexaco	Gene Kouba & Joseph Shin	Numerical Simulation of a Water/Oil Dispersion in a Distribution Manifold
Krebs Engineers	Tim Olson & Mark Hoyack	Numerical Simulation of Solid/Liquid Separation in a Hydrocyclone

1.9 Other Industrial Advisors, Second Year

Company	NSF/CRCD Advisors
AEA Technology	Jeffery Henning
Bechtel	Brigette Rosendall
Dow Chemical	Paul Gillis
DuPont	Karsten Keller
ExxonMobile	Stephen Lyons
Proctor & Gamble	Savas Aydore
Fluent	Barbara Hutchings, Ahmad H. Haidari, Richard LaRoche Kumar Dhanasekharam & Sandeep Sovani

2. Activities and Findings

2.1 Major Activities: Project Milestones and Project Calendar, Second Year

Fifth Quarter (December 2000-February 2001)

December 2000–January 26, 2001: Faculty participants prepared final NSF/IGERT proposal in support of a continuation of the NSF/CRCD initiative on multiphase transport phenomena. This proposal was unsuccessful.

January – February 2001: Randy Russell, who is the Web-Based Curriculum Manager assigned to the NSF/CRCD project by the Virtual University Technology Group at Michigan State University, established a preview page for the NSF/CRCD project (www.vu.msu.edu/preview/eng-mtp). This web site provides a means to disseminate completed project results and to recruit students for 2002. It also provides password entry into the course Web site presently undergoing β-testing (http://www.eng-mtp.vu.msu.edu/web/).

February 2001: The results developed by the undergraduate design teams during the first year are posted on the NSF/CRCD web site for industrial review. These projects will be further developed by CFD design groups during the summer.

Sixth Quarter (March 2001- May 2001)

- Chase, Mohan, Petty, Parks, and Zhuang develop revisions to the MTP Internet Course.
- Faculty participants and graduate students further develop academic case studies (see first year annual and Internet site).

Seventh Quarter (June 2001- August 2001)

- Faculty Planning and Review Session at Michigan State University (June 1–3 & 7–8, 2001)
- NSF/CRCD CFD Summer Workshop at Michigan State University (June 4 –5, 2001; see agenda below)
- Industrial Advisory Board Meeting & NSF/CRCD Multiphase Transport Phenomena Symposium, Kellogg Center, Michigan State University (June 6–7, 2001: see agenda below)
- Case study review at MSU (July 2001 see agenda below).

Eighth Quarter (September 2001- November 2001)

- Revision of industrial CFD case studies
- CFD case study presentations by undergraduates at 2001 AIChE Meeting in Reno, NV

Second Year Workshop Agenda

June 1-9, 2001
CFD Multiphase Transport Phenomena Workshop
Michigan State University

Friday, June 1

1:30 – 3 P.M., Owen Graduate Center Lobby, Room Assignments
3 – 5 P.M., Room 2150 EB, Workshop Orientation
6 – 8 P.M., Room 2150, Review of CFD Case Studies

Saturday, June 2

8:30 –10 A.M., 2150 EB/1328 EB, Division of Engineering Computing Services
10 – Noon, 2150 EB/1328EB, Transport Phenomena/CFD Workshop: Part I
1:00 – 3:00 P.M., 2150, Transport Phenomena/CFD Workshop: Part II

Sunday, June 3

1:30 – 6 P.M., 2150 EB/1328 EB, Transport Phenomena/CFD Workshop, Part III

Monday, June 4

8:30 – Noon, 2150 EB/ 1328 EB, Transport Phenomena/CFD Workshop, Part IV
1:30 – 6 P.M., 2150 EB/ 1328 EB, Transport Phenomena/CFD Workshop, Part V

Tuesday, June 5

8:30 – 10:00, 2150 EB, Teamwork
10:30 – 5 P.M. 2150 EB/1328 EB, Breakout Sessions: CFD Case Studies

Wednesday, June 6

7:30 A.M. – 5 P.M., Kellogg Center, Big Ten Room, Industrial Review & MTP Symposium
6:30 – 9 P.M., Kellogg Center, Corniche Room, Faculty/Industry Review Meeting

Thursday, June 7

8:30 A.M. – 5:30 P.M., 2150 EB, Fluent Training Session I & II
6:30 P.M. Meet at Olin Center to attend baseball game.

Friday, June 8

8:30 A.M. – 5:30 P.M., 2150 EB, Fluent Training Session III & IV

Saturday, June 9

8:30 – 10:30 A.M., 2150 EB, Fluent Training Session V
11 – Noon, Summer Workshop Evaluation and Closure

Symposium on Multiphase Transport Phenomena

June 6, 2001
1:30 – 5:00 P.M.
Kellogg Center, Big Ten Room C

André Bénard, Symposium Moderator

1:30 –2:00
Solid/Liquid Separation: Can CFD Help?
Karsten Keller
DuPont Central Research & Development

2:00– 2:30
Erosion/Corrosion Predictions in Multiphase Flow
Siamack Shirazi
The Department of Mechanical Engineering
The University of Tulsa

2:30 – 3:00
Optimization of Reservoir Production and Surface Operations
Stephen Lyons
ExxonMobil Upstream Research Company

3 – 3:30, Break

3:30 – 4:00
Hydrocyclone Inlet Design Analysis
Tim Olson
Krebs Engineers

4:00-4:30
Delayed Coking Furnace Tube Model
Keith Wisecarver
The Department of Chemical Engineering
The University of Tulsa
(cancelled due to weather conditions)

4:30-5:00
A Sample of Multiphase CFD Applications at Dow Chemical
Paul Gillis
The Dow Chemical Company

2001 NSF/CRCD CFD Design Teams

Pharmacia Corporation
Mixing of Suspensions in a Tank
Design Team A, 2001
Captain: Andrew Yoder
Assistants: Christina Berger, Yo Kim, and Carl Rose
Faculty Mentor: Charles Petty
Industrial Mentor: Mark Widman

The Trane Company
Distribution of Two-Phase Refrigerant in Heat Exchanger Tubes
Design Team B, 2001
Captain: Figen Lacin
Assistants: Dina El-dein, Nick Lynn, and Dilip Mandal
Faculty Mentor: Mei Zhuang
Industrial Mentor: Ray Rite

Eastman Chemical Company
Slurry Bubble Column
Design Team C, 2001
Captain: Brian Raber
Assistants: Kathryn Baker, Troy Hendricks, Hongmin Li, and Sara Vermillion
Faculty Mentor: George Chase
Industrial Mentor: Kevin Fontenot

Chevron
Performance of a Large Tank Separator
Design Team D, 2001
Captain: Luis Gomez
Assistants: Floyd Hammond, Steve Leibrandt, & Jose Severino
Faculty Mentor: Ram Mohan
Industrial Mentor: Gene Kouba

Krebs Engineers
Optimization and Comparison of Hydrocyclone Shapes
Design Team E, 2001
Captain: Luwi Oluwole
Assistant: William Wehbe
Faculty Mentor: Steven Parks
Industrial Mentor: Tim Olson

Student/Faculty Retreat

CFD Case Study Review
July 27 & 28, 2001
Michigan State University

Friday, July 27

Willy Room, Kellogg Center

4 – 7:00 P.M. Overview of CFD Case Studies

- Introductions and review of agenda followed by PC power point presentation of case studies (20 minutes for each presentation; 10 minutes for questions)
- Adjourn at 7 P.M.

Saturday, July 28

Video Taping, Room 1208 EB

- 9:00 A.M. to 9:30, Tim Elkins, MSU Broadcasting Services
- 9:30 to 10:00, Ram Mohan, Gas/Liquid Two-Phase Flows
- 10 to 10:30, George Chase, Flow Through Porous Media

Break (15 minutes)

- 10:45 to 11:15, Team A, Pharmacia
- 11:15 to 11:45, Team B, Trane

Lunch Break (75 minutes)

- 1:00 to 1:30 P.M., Team C: Eastman Chemical
- 1:30 to 2:00, Team D: Chevron
- 2:00 to 2:30, Team E: Krebs Engineers

Break (60 minutes, Return to the Kellogg Center)

Willy Room, Kellogg Center

- Round Table Discussion of CFD Case Studies
- Final Written Report Format & Deliverables, C. Petty

2.2 Major Findings

The five CFD design projects were completed during the 2001 summer internship. A brief abstract of each project follows. The final reports will be placed on the NSF/CRCD web site. These projects will be used as CFD case study examples for the multiphase transport phenomena Internet course offering during the 2002 summer term, July–August 2002.

Numerical Simulation of a Solid/Fluid Suspension in an Enclosed Tank

C. R. Berger, Y. C. Kim, C. P. Rose, and A. R. Yoder
The Department of Chemical Engineering and Materials Science
Michigan State University
East Lansing, Michigan 48824

Abstract

Maintaining a uniform suspension of solid drug particles in a feed tank is an important unit operation in the pharmaceutical industry. One way to accomplish this task is to use a perforated vibrating plate situated on the axis and near the bottom of the tank. The perforations in the plate are conical in shape and create a jet-like flow through each hole as the plate moves up and down.

In this study, the pumping action of the plate is simulated by an axisymmetric round jet. The simulation examines the influence of the liquid level, the position of the momentum source, and the jet velocity on the spatial uniformity of a suspension of 10 μm-diameter solid particles (density = 1,193 kg/m^3). The results indicate that 1) once mixed, the solid/fluid suspension remains well mixed for the range of conditions studied; and, 2) the jet velocity influences the mixing time significantly whereas the axial location of the round jet and the liquid holdup have only a minor, but noticeable, impact on the extent of mixing.

Background

Maintaining a spatially uniform suspension of solids in a low viscosity fluid is a challenging unit operation in the pharmaceutical industry. An important example is the suspension of Depo-Provera® (medroxyprogesterone acetate) in water. Depo-Provera® is insoluble in water and has a density of 1,193 kg/m^3. Individual particles are spherical and the particle size distribution has a mean diameter of approximately 10 μm. The maximum particle diameter is below 20 μm. In some applications, the carrier phase may contain surfactants, suspending agents, and preservatives.

Engineers at Pharmacia in Kalamazoo, Michigan use a vibrating plate to suspend solids in an aqueous carrier phase (personal communications with Mark Widman of Pharmacia). The continuous and dispersed phases are combined in a pre-mixer. The suspension is transferred to a 26"-diameter feed tank that supports the filling operation (see Figure 1, figures wil;l be shown in the final report). The tank is initially charged with 40 gallons (151 λ) of suspension. The initial liquid level in the tank is about 45 cm. The average concentration of the dispersed phase in the batch is 15 vol.%.

While the feed tank is moved to the filling line, which takes about 15 min., particles settle to the bottom of the tank and the suspension concentration becomes spatially nonuniform. A relatively short resuspension stage precedes the vial filling stage. During the vial filling stage, the suspension is withdrawn from the bottom of the tank at 600 mλ/ min. and returned to the tank at 300 mλ/min. The difference of 300 mλ/min. is sent to a filling line where it is injected into one-milliliter vials. The volume fraction of the dispersed phase in the vial should be 15 (± 1.05) %. The 40-gallon feed tank (see Figure 2) can support a filling operation for about eight hours.

A vibromixer provides a relatively simple means to suspend a solid phase in a low viscosity fluid. This type of mixer consists of a shaft and a plate with conical holes. The number of holes depends on the application. For example, a 60-hole plate, which has a diameter of about 10.5-cm., is used to suspend Depo-Provera® particles in a 40-gallon tank. If the conical holes are oriented so the minor diameter is on top, then an upward jet-like flow is produced as the vibrator executes a downward stroke. During the upward stroke, low speed fluid is entrained from the contiguous surroundings near the top of the plate and enters the diverging cone (see Figure 3). The diverging cone acts like a diffuser and does not produce a jet-like flow towards the bottom of the tank. As the plate moves up and down, the suspension is pumped through the perforations forming multiple jets. The frequency of the motion is 60 Hz (i.e., 60 cycles/sec) and the peak-to-peak motion can be manually set in the range 0.051 cm to 0.254 cm. Thus, an upward convective current is produced on the axis and returns to the bottom of the tank near the wall. This circulation patterns can be reversed by reversing the installation of the perforated plate.

Numerical Simulation of Flow within a HVAC Header

D. A. El-dein[2], F. Lacin[1], N. F. Lynn[1], and D. K. Mandal[1]
[1]The Department of Mechanical Engineering
[2]The Department of Chemical Engineering and Materials Science
Michigan State University
East Lansing, Michigan 48824

Abstract

The purpose of a header in a heating, ventilation and air conditioning (HVAC) system is to uniformly distribute a refrigerant to multiple evaporator tubes without changing the quality of the two-phase fluid. In this CFD case study, a large diameter vertical tube with equally spaced 12-mm diameter evaporator tubes serves as the header, or flow distribution manifold. The primary goal of this CFD simulation is to determine the backpressure needed at the outlets of each branch tube to satisfy the foregoing HVAC system requirements. A secondary goal is to study the effect of droplet diameter on the quality of the refrigerant delivered to each evaporator tube.

The multiphase turbulent flow within the distribution manifold is simulated using a two-fluid model supported by CFX 4.3 and an algebraic slip mixture model supported by Fluent 5.5. Both simulations show that internal secondary flows and gravitational effects cause liquid droplets to accumulate in the lower portion of the header. The CFD simulations provide new insights into possible design changes that may improve the performance of the distribution manifold.

Background

A header in a HVAC system is designed to deliver an equal amount of two-phase refrigerant (1,1,1,2-tetrafluroethane, R134a) to several evaporator tubes at the same quality. As illustrated by Figure 1(figures and tables will be shown in the final report), the header is located between the thermal expansion valve and the evaporator. The maximum pressure that can be produced by the HVAC compressor is 1,100 kPa (~ 160 psia). A thermal expansion valve upstream of the header produces a two-phase saturated fluid containing liquid drops as small as 5 μm and as large as 100 μm; the mean diameter of the dispersed phase is about 20 μm.

Figure 1 gives a summary of the thermophysical properties of the refrigerant entering the distribution manifold. The temperature of the saturated two-phase fluid is 282 ^{o}K (~ 48 °F) and the pressure is 400 kPa (i.e., 58 psia or 4 atm). The density of the saturated liquid phase is 1,154 kg/m^3 and the density of the saturated vapor phase is 21.72 kg/m^3. The feed stream to the header is 93% vapor by volume (20% vapor by mass). The density of the two-phase mixture is 101 kg/m^3.

Engineers at The Trane Company in La Crosse, Wisconsin are exploring different designs for HVAC headers. As illustrated by Figure 2, one approach is to use a vertical tube with fifteen equally spaced 12-mm diameter branch tubes as a header. The center-to-center spacing between the branch tubes is 32mm. The cross sectional area of the header is 16.96 cm^2, which is equal to the total cross sectional area of the fifteen 12mm-diameter evaporator tubes. The diameter of the vertical tube is 46.48 mm and the length of the header is at least 475 mm long.

The mass flow rate of the two-phase mixture to the fifteen-tube distributor is 0.40 kg/s, or ~14.4 m^3/hr. The refrigerant is introduced at the top of the 46mm-diameter distribution manifold with a bulk average velocity equal to 2.237 m/s. Ideally, each evaporator tube should receive the same amount of refrigerant (i.e., 0.0267 kg/s) with a quality equal to 93% vapor by volume. If this occurs, the cross sectional average velocity is also equal to 2.237 m/s in each of the 12mm-diameter evaporator tubes. Within the large vertical tube, the cross sectional average velocity decreases from 2.237 m/s at the top to approximately 0.153 m/s just above the evaporator tube at the bottom.

Numerical Simulation of a Bubble Column

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The University of Akron
Akron, Ohio 44325
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Abstract

Large slurry bubble columns (SBC) are important in the chemical and biochemical industries where three-phase reactions are common. SBC-reactors are used by Eastman Chemical Company in Kingsport, Tennessee to manufacture specialty chemicals. The purpose of this project is to determine the effect of sparger ring diameter, D_S, and gas flow rate, Q_G, on the liquid phase residence-time-distribution in a bubble column. In this CFD study, an algebraic slip mixture model (ASMM) is used to simulate an air/water mixture in a column of diameter D (= 2.4m) and height H (= 19.2m). The volume of the column, V, is approximately 91 m^3. The volumetric flow rate of the liquid phase, Q_L, is about 89 m^3/h; the gas rate, Q_G, is varied from ~800 m^3/h to ~ 2,400 m^3/h. Thus, for the conditions studied, the superficial mean residence time of the liquid phase is about 3,600s whereas the superficial mean residence time for the gas phase ranges from 137s at the high gas rate to 410s at the low gas rate.

Simulations were developed for D/D_S from 8/3 to 8/6. The aspect ratio of the column was fixed at H/D = 64/8. The results show that the mean residence time of the liquid phase is approximately 700s for $D/D_S \cong 8/4$. This implies that the liquid holdup in the column is about 17vol.% of the mixture volume. The simulation reveals that regions of very high concentrations of the dispersed phase develop in an annular zone above the sparger and at the top of the column. This segregation of the air and water phases limits the contact time available for mass transfer.

Background

The unit operation being investigated in this report is a slurry bubble column (SBC). SBC's are currently being used in the chemical and biochemical industries because of the many advantages they offer in relationship to the more traditional unit operations. Some advantages include energy savings and low maintenance requirements. Without any moving parts, SBC's are inexpensive to maintain and operate. The wide range of SBC applications include reactions being carried out that require specific environments and/or residence times to pure traditional mixing applications.

The research described here is motivated by the complicated flow within SBC's and the lack of published research on the mixing profiles within SBC's. A better understanding of these flow and mixing patterns will result in process optimization. In industry today, empirically based equations are used for the design and scale-up of SBC's. These empirical correlations are usually specific to the columns' geometry, and may be a function of the materials being used in the columns. Correlations based on more generic SBC's should be applicable to most, if not all, SBC's. One particular area of interest is how gas sparger ring diameter can affect the mean residence time within a slurry bubble column. Results of this investigation could help in the design of more efficient columns.

Most SBC's are aqueous based and use air as the sparging gas; the model developed here uses water as the liquid phase and air as the gas phase. Further considerations include temperature and solids loading effects on parameters such as mixture viscosity. These latter effects are not investigated in this work. Furthermore, the multiphase algebraic slip mixture model (ASMM) used here cannot evaluate heat effects, so the simulations of the column operation are evaluated at room temperature. (Fluent User's Manual Section 15.4.2).

CFD Study of a Water/Oil Dispersion in a Distribution Manifold

L. E. Gomez[1], F. A. Hammond[1], S. J. Leibrandt[2], and J. G. Severino[1]
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The University of Tulsa
Tulsa, Oklahoma 74104
[2]The Department of Mechanical Engineering
Michigan State University
East Lansing, Michigan 48824

Abstract

Wet crude oil gravity separation tanks play an essential role in the production of crude oil and are often deployed upstream of a desalting operation. The capacity of these tanks may be as large as 80,000 barrels (13,392 m^3) and may process 60,000 bpd (9,600 m^3/day) of wet crude oil containing 20vol.% water. As an oil field ages, the water cut increases and the separation performance of the gravity separator declines. Engineers at Chevron in Houston, Texas have recently simulated the performance of large-scale gravity separators to better understand the relationship between water cut and separation performance. An important assumption employed in previous studies is that the wet crude oil is uniformly distributed near the bottom of the tank.

In this study, the flow of the water/oil mixture through a skeleton-like spreader system consisting of a 24"-diameter backbone pipe with smaller 12"-diameter branch lines is simulated by using an algebraic slip mixture model. Multiple effluent slots are uniformly positioned along the individual branch lines. The simulation examines the influence of feed rate on the maldistribution of the water/oil mixture within the spreader geometry. The calculations show that the pressure in the large feeder pipe increases in the direction of flow and that a nonuniform distribution of water and oil occurs due to secondary flows associated with flow splitting into the smaller branch lines. The current study predicts the flow rate, the water/oil ratio, and the pressure drop across the small slots in the branch lines. This information is needed to estimate the size of the water drops introduced into the gravity separator.

Background

This study is for a customer who owns a number of wet crude oil gravity separation tanks and is considering the operation of the tanks at appreciably higher throughput. These large tanks are used to separate water from crude oil before it is returned to the environment. After the water is removed from the oil, the stream is sent to desalters. As the 60,000 bpd feed contains around 20% water by volume, this is merely a bulk separation process and does not concern itself with the small amounts of atomic-scale mixing of the water and oil. Water and oil will readily separate if given the chance, and that is what the gravity tanks attempt to facilitate.

The overall dimensions of the tank subject to this study are 33 meters in diameter and 15 meters in height. The tank storage capacity is about 80,000 barrels and can handle up to approximately 185,000 barrels per day. There are two main pipe networks inside the tank. One network is the *oil/water inlet spreader system* located 1.5 meters above ground, and the other is the *outlet pipe network* located at 7.1 meters above ground. A side view of the tank and pipe network systems is shown in Figure 1(figures and tables will be presented in the final report). The inlet pipe network consists of a main feeder pipe of 26” in diameter and has a length equal to the tank diameter. At regular intervals of 5.4 meters apart, two 12” pipes are attached to each side of this pipe and extend closely to the edge of the tank. A total of ten (i.e. five pairs) such 12” branch pipes of different lengths form this network. The oil/water mixture leaves the 12” branch pipes through oval-shaped slot nozzles located at the underside of the branch pipes. A top view of the inlet spreader network is shown in Figure 2. There are 42 slots in shorter pipes, 52 in the medium-size pipes and 56 in the longer pipes located at the center of the tank. The slots are 20mm in width and 50mm in length, as shown in Figure 3. Pure crude oil leaves the tank through the *outlet pipe network* that consists of four 24” pipes of 15.7 meters in length, while water is drained out from a water sump located at the bottom of the tank, about 2.6 meters away from the edge and is 1.22 meters in diameter. Table 1 summarizes the current geometric setup values of the separator components.

The oil/water dispersion is introduced through a network of pipes located near the bottom of the separation tank. The goal of the spreader system is to provide a uniform oil/water dispersion over the cross sectional area of the tank. Current study focuses on investigating a possible mal-distribution of oil water and droplet size inside the spreader network. The feed rate to the 26″-diameter inlet pipe is about 60,500 bpd (9,620 m^3/day). As provided in the customer service report, the bulk average velocity at the beginning of the feeder line is 0.3253 m/s at the end. The flow is in the turbulent regime throughout the 26″-diameter pipe and goes through transition in outer regions of spreader pipes. The slotted effluent nozzles have an equivalent cross sectional area of approximately 0.001314 m^2. General flow conditions and properties are summarized in Tables 2 and 3.

Influence of Cone Angle and Capacity on Hydrocyclone Separators

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[2]The Mechanical Engineering Department
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Summary

Hydrocyclone classifiers are used in closed circuit grinding operations to control the size distribution of mineral ores prior to flotation. Recently, Krebs Engineers of Tucson, Arizona introduced a new class of hydrocyclone classifiers with a double cone design. The new design, referred to as the gMAX® cyclone, has a relatively low separation cut size (~ 60μm) and a high capacity (~ 77m^3/h). In this CFD study, the turbulent flow field within a 254mm-diameter gMAX® cyclone is simulated using the standard k-ε model for the Reynolds stress. The entrainment of an air core on the axis of the hydrocyclone is eliminated in the simulation by imposing a spatially uniform backpressure on the overflow and underflow streams. A discrete-phase particle tracking technique is used to evaluate the separation performance of the hydrocyclone classifier.

The flow patterns within a 10.5°- and 20°- single cone are compared with the flow patterns that develop within the new 20°/6°-double cone design. Simulations for the three hydrocyclones are developed for two feed rates: 35 m^3/h and 60 m^3/h. The results show that the volumetric flow split is independent of capacity and shape, with approximately 75 vol% of the feed stream exiting through the overflow nozzle. The predicted pressure drop across the hydrocyclone is much lower than observed in field tests, but this type of result is symptomatic of the turbulence model employed. Although the D_{50}-cut size of the separator predicted by the simulation is larger than expected, qualitative comparisons among the three designs are self-consistent. The simulation

shows that the D_{50}-cut size decreases with an increase in the inlet velocity and, most significantly, that the D_{50}-cut sizes for the 20° cyclone and the gMAX® cyclone are essentially the same for a feed rate of 60 m^3/h.

Background

The geometry of a hydrocyclone has a significant impact on the internal flow behavior of the continuous phase and, thereby, influences the separation of the dispersed phase (Bradley, 1965; Svarovsky, 1984). Figure 1 (figures and tables will appear in the final report) gives a perspective view of a typical hydrocyclone. The hydrocyclone has a single tangential/involute inlet that distributes the feed near the end wall between the vortex finder and the sidewall. The underflow and overflow withdrawal nozzles are at the opposite ends of a frustoconical chamber and are situated on the symmetry axis. The swirling flow within the separator causes a heavy dispersed phase to move outward and a light dispersed phase to move inward. The core flow surrounding the axis is directed toward the vortex finder and is removed through an overflow withdrawal nozzle. The outer flow near the wall of the separator is directed toward the apex of the cone and is removed through an axially situated cylindrical nozzle

There are many hydrocyclone applications. One such application in a mineral processing plant relates to the closed circuit grinding of mineral ore. The ore, after mining, undergoes a series of crushing stages and then grinding in order to liberate valuable mineral products. Examples include Cu, Au, Ag, Pb, Zn, iron ore, phosphate, and limestone. Primary grinding is performed in a ball mill where a slurry of approximately 1000 mm ore is ground to a state characterized by a particle size distribution (PSD) in which 80% of the ground material is between 25 and 200 mm. After the ground slurry exits the ball mill, it is pumped to a hydrocyclone with the intent to recycle the underflow to the ball mill along with the fresh feed. Thus, the hydrocyclone in this operation behaves as a classifier. Particles, which are too coarse for effective subsequent downstream processing, are returned to be re-ground, while particles below a critical size are allowed to pass downstream via the overflow. In most cases, the overflow product from the hydrocyclone goes to a flotation process. In other cases, a magnetic separation process follows grinding.

A diagram of this process for the specific application of copper production is illustrated in Figure 2. The composition of the ore is varied, but, for this application, the typical ore is less than 1% copper (chalcopyrite, chalcocite) and 99% silicates. The hydrocyclone overflow that proceeds to the flotation unit operation is upgraded to about 30% copper, and this then goes to the smelter/refiner, which yields 99.999% copper. The feed to the hydrocyclone usually has a solids weight composition of up to ~50%, with the specific gravity of the particles ranging from 2.5 to 2.7 [Olson, 2001b].

The application described above constitutes the focus of this study. Due to the nature of its function in the overall process, it is important to understand the separation performance of the hydrocyclone. That is, accurately predicting the separation parameter D_{50} is key in being able to properly select a hydrocyclone which neither passes excessively large particles downstream nor needlessly recycles smaller particles (which are already suitable for downstream processing). Previous studies have been conducted on the effects of parameters such as the configuration of the inlet section on the resulting hydrocyclone performance [Oluwole, *et al.*, 2001]. Therefore, this study addresses the effect of the inlet Reynolds number and hydrocyclone cone angle on separation performance.

2.3 Opportunities for Training and Development

2.3.1 AEA Technology Engineering Software, Inc. and Fluent, Inc. provided CFD training for the NSF/CRCD participants (see CFD summer workshop agenda above).

2.3.2 Michigan State University hosted a one-week MTP/CFD Summer Workshop and a one-day MTP Symposium during the 2001 CFD summer workshop.

2.4 Outreach Activities

An NSF/CRCD Internet course on Multiphase Transport Phenomena was offered during the period September11– November17, 2000 (see first year annual report). This experimental course was restricted to NSF/CRCD students and selected graduate students at MSU (three virtual contact hours per week for 10 weeks; 2 academic credits). This course has undergone significant revisions and will be offered during the 2002 summer term, July 1-August 15.

3. Publications and Products

3.1 Presentations and News Events (Cumulative for project)

1. “Multiphase Transport Phenomena Course Surges Beyond University Walls”, EVENTS, No.147, College of Engineering, Michigan State University, February 2000.

2. “NSF/CRCD Multiphase Transport Phenomena: The Use of Commercial Computational Fluid Dynamic Tools to Support Engineering Design”, presented by S. Parks and M. Shao, Michigan State University Faculty Computer Fair, March 29, 2000.

3. “NSF Combined Research Curriculum Development on Multiphase Transport Phenomena”, presented by Charles Petty, North Central American Society for Engineering Education, Kellogg Center, Michigan State University, March 31, 2000.

4. “NSF/CRCD Multiphase Transport Phenomena Curriculum Development”, presented by C. Petty, Poster Session on Frontiers in Chemical Education, Pasadena Room, AIChE Annual Meeting, Los Angeles, CA., November 13, 2000.

5. “NSF–CRCD Project on Multiphase Transport Phenomena”, presented by R. Mohan, XXI Oklahoma AIAA ASME Symposium, The University of Tulsa, February 24, 2001.

6. “NSF/CRCD: Multiphase Transport Phenomena”, G. Chase (presenter), E Evans, C. Petty, M. Zhuang, K. Jayaraman, A. Benard, M. Amey, R. Mohan, O. Shoham, S. Shirazi, K. Wisecarver**,** Session 1526, Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition, Copyright © 2001, American Society for Engineering Education, Albuquerque, New Mexico, June 24 –27, 2001.

7. “First Year Annual Report on NSF/CRCD 9980325: Multiphase Transport Phenomena Curriculum Development”, Charles A. Petty, Principal Investigator, Michigan State University (Lead University) in cooperation with The University of Akron, The University of Tulsa.

8. “NSF Combined Research Curriculum Development on Multiphase Transport Phenomena: A Web Base Teaching Adventure”, Marilyn J. Amey (speaker), Steven M. Parks, Charles A. Petty, Mei Zhuang, George G. Chase, Ram S. Mohan, Symposium on *Web-Based Distance Learning*, 2001 Annual AIChE Meeting, November 4-9, Reno Hilton, Reno, NV.

9. “NSF Combined Research Curriculum Development on Multiphase Transport Phenomena”, Charles A. Petty (presenter), poster session on education, 2001 Annual AIChE Meeting, November 4-9, Reno Hilton, Reno, NV.

10. “NUMERICAL SIMULATION OF A SOLID/FLUID SUSPENSION IN AN ENCLOSED TANK” , Paper No. 215-6a Berger, Christina R. (presenter), Yo Chan Kim, C.P. Rose, A.R. Yoder, Charles Petty, Department of Chemical Engineering, Michigan State University, East Lansing, MI and Mark Widman, Pharmacia, Kalamazoo, MI**,** Group 6: North American Mixing

Forum**,** undergraduate poster session, 2001 Annual AIChE Meeting, November 4-9, Reno Hilton, Reno, NV.

11. "NUMERICAL SIMULATION OF FLOW WITHIN A HVAC HEADER", El-dein, Dina (Presenter) Chemical Engineering Department, Michigan State University, East Lansing, MI; Figen Lacin, Nick F. Lynn, Dilip Mandel, and Mei Zhuang, Department of Mechanical Engineering, Michigan State University, East Lansing, MI; and Ray Rite, The Trane Company, La Crosse, WI, Group 10: Computing and Systems Technology, undergraduate poster session, paper No. 215-10a, 2001 Annual AIChE Meeting, November 4-9, Reno Hilton, Reno, NV.

12. "NUMERICAL SIMULATION OF A BUBBLE COLUMN", Hendricks, Troy (Presenter) and K.M. Baker, Department of Chemical Engineering and Materials Science, Michigan State University, East Lansing, MI; S.M. Vermillion (presenter), H. Li, B.P. Raber, and George Chase, Department of Chemical Engineering, University of Akron, Akron, OH; and Kevin Fontenot, Eastman Chemical, Group 20: Catalysis and Reaction Engineering, undergraduate poster session, paper No. 215-20b, 2001 Annual AIChE Meeting, November 4-9, Reno Hilton, Reno, NV.

13. "NSF Combined Research Curriculum Development on Multiphase Transport Phenomena", Steven M. Parks, Charles A. Petty (presenter), Mei Zhuang, Marilyn J. Amey, George G. Chase, and Ram S. Mohan, 2002 ASEE Annual Conference & Exposition, Vive Le Engineer! Montréal, Quebec, Canada, June 16-19, 2002.

14. "NSF Combined Research Curriculum Development on Multiphase Transport Phenomena: A CFD Design Adventure", Steven M. Parks and Charles A. Petty (presenter), Mei Zhuang, Marilyn J. Amey, George G. Chase, and Ram S. Mohan, International Conference on Engineering Education ICEE-2002, UMIST, Manchester, Great Britain, August 18-22, 2002.

3.2 Web Sites

Randy Russell and Chanelle Embrey have established a preview page for the NSF/CRCD project (www.vu.msu.edu/preview/eng-mtp). This web site provides a means to disseminate completed project results and to recruit students. It also provides password entry into the Internet course site presently undergoing β-testing (http://www.eng-mtp.vu.msu.edu/web/). The web site also facilitates communication among the 43 or more NSF/CRCD faculty participants, students, and industrial participants (see above) by providing photographs, telephone numbers, e-mail addresses, web page connections, and a WebTalk bulletin board.

4. Contributions and Assessment

The impact and significance of this NSF/CRCD project will be summarized in the final report.