FOURTH EDITION

A WORKING GUIDE TO Process Equipment

Norman P. Lieberman
Elizabeth T. Lieberman

Mc Graw Hill Education

A Working Guide to Process Equipment

Norman P. Lieberman
Elizabeth T. Lieberman

Fourth Edition

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To the union of two people
Weathering life's storms together
Watching the lightning
Waiting for the thunder
In friendship, In partnership
In love

To the Memory of
Our Friend and Colleague

Gilles de Saint Seine
Process Engineer
Total-Fina-Elf, France

It's more than losing a friend, it seems as if Liz and I have lost part of ourselves, but we will always remember his gentle determination and insightful work, his love of family and consideration for his colleagues, and not least his marvelous wit.

This book is dedicated to our parents:

Elizabeth and Tom Holmes, innovative engineers, courageous under fire at war and in peace.

Mary and Lou Lieberman whose enduring strength and fortitude have been little noted, but long remembered.

About the Authors

Norman P. Lieberman is a chemical engineer with 50 years of experience in process plant operation, design, and field troubleshooting. An independent consultant, he troubleshoots oil refinery and chemical plant process problems and prepares revamp designs. Mr. Lieberman teaches 20 seminars a year on "Troubleshooting Process Plant Operations" and has written eight books on plant process operations and problems.

Elizabeth T. Lieberman is a chemical engineer with more than three decades of experience in the process industries. She works as a consultant troubleshooting oil refinery and chemical plant process problems. Ms. Lieberman also has experience in ceramic clay processing, refractories processing, and the conveyance of slurry flow.

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Foreword

The forest has largely reclaimed the Amoco Refinery in Destrehan, Louisiana. A large sugar maple sprouts from a long since forgotten control room. If one didn't know, the delayed coker drum structure might be mistaken for a ruined temple. Brick chimney stacks rise defiantly above the feathery tops of the cypress trees.

The process vessels were uprooted in 1955 and shipped to the Amoco Refinery in Texas City. Odd bits of piping and valves have sunk into the swamp. A half century of gentle, but persistent effort by Mother Nature has partly reclaimed this bit of earth for the natural world.

The area is fenced and closed to the public. Well test points dot the fence line. After 50 years, someone is still monitoring the ground water seepage for escaping aromatics and other cancer-causing chemicals. I've hiked through this area a dozen times. Never have I seen a rabbit or a snake or an alligator or a nutria or a deer. The large pond in the center of the site is devoid of fish, turtles, and frogs.

Some day soon—in 20 years or 100 years—the Mississippi River, which flows just across the River Road, will breach its levee and clean up this mess. Or nature may get really angry and toss the Gulf of Mexico over Destrehan with a category 5 hurricane. It's only a matter of time.

Same with the other problem. CO_2 is increasing at 2 ppm a year. Another 3 or 4°F will make large parts of the earth uninhabitable. Exploitation of heavy hydrocarbon deposits in Alberta and Venezuela can only increase the 2 ppm CO_2 growth rate. This can go on for another 20 years or another 100 years. Then Mother Nature will take serious corrective action to restore natural equilibrium. It's only a matter of time.

What can you do? A few ideas:

- Close hand valves on steam turbines
- Reduce pump impeller sizes
- Suction throttle compressors rather than spillback recycle gas

- Minimize tower pressure to maximize relative volatility and minimize reflux rates
- Keep gas-fired turbine rotors clean
- Avoid afterburn in heater convective sections
- Don't justify new projects to replace existing equipment that just needs maintenance
- Read this book

Sooner, rather than later, nature may get really angry and eliminate the fundamental problem. Time is not on our side.

Other Books by Norman P. Lieberman

- *Troubleshooting Refinery Processes* (1980 edition)
- *Troubleshooting Natural Gas Processing*
- *Process Design for Reliable Operations* (3rd edition)
- *Troubleshooting Process Plant Control*
- *Process Engineering for a Small Planet*
- *Process Equipment Malfunctions*
- *Troubleshooting Process Operations* (4th edition)
- *Troubleshooting Vacuum Systems*
- *My Race Against Death: The Story of One Runner Who's Running Further and Faster with Age, But Who Refuses to Listen to Reason*

The best method to purchase any of these texts is Amazon. *A Working Guide to Process Equipment* is the most popular of the above list. *Troubleshooting Process Operations* is the best text for refinery-specific applications. Young engineers and operators find *Troubleshooting Process Plant Control* the most helpful. Check our website for details: www.lieberman-eng.com.

Preface to the Fourth Edition

Buried deep in our genetic heritage, hidden in an obscure string of DNA, is coding for Process Equipment Operations. An instinctive desire to apply energy to transmute the properties of naturally occurring materials into other, more useful forms. Like cooking food; or fusing clay into ceramic pots; or reacting sulfur with air to produce sulfuric acid; or transmuting lead to gold.

Looking back on 50 years as a process engineer, the most satisfying period of my career was devoted to converting gas oil into viscous polypropylene via cracking reactions and refrigeration.

The gene that codes for operation and design of process equipment, such as distillation columns and fired heaters, is a recessive gene. Only one out of 40 individuals have inherited this genetic code for process equipment operations as a dominant trait.

Should you wish to determine if your child has inherited this genetic makeup for process equipment operations, observe if the child:

- Is fascinated by fire
- Tries to dam and divert little streams
- Is attracted by boiling water
- Asks what makes a windmill turn

Thus, only one out of 40 people have the potential to evolve into process engineers or operators. The rest will become Directors of Human Resources or Maintenance Superintendents.

My older sister often asks, "Norman. You're over 72. When are you going to retire? You're too old to be climbing distillation towers. You'll fall off one of these days."

"Arline," I explain, "I can't retire. It's in my blood."

"Norman, you're crazy! Everyone else in our family retired in their 60s. It couldn't be in your blood. Dad moved to a retirement village when he was only 62."

"You don't understand, Arline. It's a recessive gene I inherited from our ancestors generations ago. I can't retire. It's part of my DNA. It's instinctive behavior. Like a beaver building a dam. Or squirrels gathering nuts in the fall. I can't retire. I'll just have to go on until the end."

Norm Lieberman

If you have questions, you can contact us at:

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Preface to the Third Edition

When I feel a gentle breeze cool against my skin, I think about the sun causing uneven heating of the earth's surface. Hot air rises; cool air rushes into the area of lower air density. Thus the wind.

When I see a sparkling stream cascading in silver bubbles over rounded pebbles, my thoughts drift to converting potential energy to kinetic energy. Our visit to the lovely wine country of the Sonoma Valley awoke within me memories of the early days of spirit distillation.

A wax candle was burning in a remote church we visited in England. How many candles would be burned to heat the air in the church by 10°F? Knowing the heat of combustion of wax and the specific heat of air, I could and did calculate that 68 candles would be consumed.

A child's brightly colored pinwheel spinning in the wind creates an irresistible urge to discourse on steam turbines. A pot of pasta boiling over on our stove is the perfect incentive to deliver a lecture, which no one wants to hear, detailing foam-induced flooding in packed towers. Suntanned skin is the perfect example illustrating the power of radiant heat transfer.

I quite realize that normal people do not have such thoughts racing continuously through their minds. I can't help myself. It's a consequence of being a process engineer for too long.

For 43 years I've been worrying and pondering about how process equipment works. For half a century I've been seeking enlightenment about mysteries of nature!

- What causes thermosyphon circulation in reboilers?
- How can a positive pressure develop in a natural draft-fired heater?

- What causes surge in centrifugal compressors?
- Why do two identical condensers, working in parallel, perform entirely differently?
- What are the hand valves on a steam turbine all about?
- How exactly does reflux improve product separation?
- Why is the seal flush pressure to a centrifugal pump the suction rather than the discharge pressure?
- What affects tray efficiency in distillation?
- Why do reciprocating compressors have adjustable unloaders?
- How can the liquid level in a drum of boiling water be measured?
- Can the oil temperature inside a pipe be measured based on the exterior pipe temperature?
- Why do some heat exchangers suddenly seem to clean themselves?

Maybe if Liz and I write all this down, I can stop thinking about these questions. We tried to do so in our first two editions, but failed. I'm still wondering and worrying. So once again we will try in this third edition of *A Working Guide to Process Equipment: How Process Equipment Works*. If you have questions, contact us at:

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- Norm@Lieberman-eng.com (email)

Norm and Liz Lieberman
Metairie, Louisiana

May 7, 2008

Preface to the Second Edition

Dear Aunt Hilda:

I hope this letter finds you well and in good spirits. How is Uncle Herb?

Incidentally, I am not a drug dealer. My mother, I fear, has told you that I make a lot of money in drugs. I sometimes consult on process engineering problems for pharmaceutical companies—but I do not deal drugs.

I know my mother told you about the drugs because she doesn't understand what Liz and I do. Also, she's still disappointed that I didn't become a doctor. I've explained what a process engineer does to Mom a hundred times. Let me try to explain it to you.

First, Aunt Hilda, process equipment is all around us:

- Gas burner in an oven
- Steam radiator
- Vacuum cleaner
- Sump pump in your basement
- Central air conditioning
- Hot water heater
- Toilet water closet
- Refrigerator

Our job is to design improvements to existing process equipment. To do this we do three things:

- Investigate the current operation of the process equipment in oil refineries and chemical plants. Based on field data, what are the actual operating parameters of a process plant?

- What are the design or theoretical operating parameters of the plant?
- What is causing the plant to perform below its theoretical efficiency and what shall be done to correct the deficiency?

To be successful, Liz and I have to understand in a fundamental way how the equipment actually works. It's true that I do a lot of work with centrifugal refrigeration compressors. However, contrary to what my mother told Mrs. Goldberg, I am not a Frigidaire repairman.

I hope this letter explains what I've been doing for the past 40 years. I definitely do not regret not becoming a doctor. I'm enclosing a copy of our book, *A Working Guide to Process Equipment: How Process Equipment Works,* for you and Uncle Herb. This really explains what process equipment is all about in a pretty simple way.

I think you would agree that an important company like McGraw-Hill would not publish such a book if they thought that I was a drug dealer. We'll see you, God willing, at the wedding in June.

All our love,
Norm and Liz Lieberman
January 4, 2003
P.S.: If you have any questions, please contact us at:

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Preface to the First Edition

November 1, 1996

Subject: How Process Equipment Works

Dear Reader:

Thank you for buying our book. We worked very hard writing it, and we appreciate your vote of confidence.

No normal person is going to read this book for fun or relaxation. It is a work book, for working people. You purchased it with the hope and faith that it can help you do a better job. You opened it with the expectation that you can read it with comprehension.

Well, we won't let you down. But, let's make a deal. We promise you that even though this is a technical book, you can read it easily, without pain, but with comprehension. After you read it, you will definitely be a better process operator or engineer. Your part of the deal is to read the whole book. This is not a reference or source book. All the chapters are tied together by threads of logic. You will really find it easier to grasp this logic if you read the chapters in sequence.

A few of the words in the text are italicized. These words are explained in the Glossary at the back of the book.

Please feel free to give us a call if there is some point you would like to discuss, or a process question you wish to ask.

Sincerely,

Norm Lieberman
Chemical Engineer

Liz Lieberman
Chemical Engineer

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Introduction

In 1983, I started teaching a three-day process equipment troubleshooting seminar to chemical engineers and experienced plant operators in the petroleum refining and chemical process industry. Since the inception of the seminar, in excess of 7000 men and women have attended the classes. The seminar is largely based on my 40 years' experience in field troubleshooting and process unit revamp design.

I have taught hundreds of seminars explaining how pumps, compressors, heat exchangers, distillation towers, steam jets, fired heaters, and steam turbines malfunction. I have explained to thousands of chemical engineers how to design trays and modify tube bundles for improved performance. More thousands of operators have listened to me expound as to how and why cavitation damages pump mechanical seals. And throughout these lectures, one common thread has emerged.

The general knowledge as to how process equipment really functions is disappearing from the process industries. This is not only my opinion but the general view of senior technical managers in many large corporations.

Chemical process equipment is basically the same now as it was in the 1930s. The trays, K.O. drums, compressors, heaters, steam systems have not changed—and probably will not change. The fundamental nature of process equipment operation has been well established for a very long time. Modern methods of computer control and process design have not, and cannot, change the basic performance of the bulk of process equipment. These tools just have made learning about the working of the equipment more difficult.

The chemical engineer has traditionally been the guardian of process knowledge. So, one would suppose that if fundamental process knowledge is vanishing, the origin of the problem may lie in our universities. Perhaps there is less of that "hands-on approach" to problems with the advent of the PC or perhaps there are just fewer people around to teach us. No one really knows.

But in this book, we have gone back to the very simplest basis for understanding process equipment. In every chapter we have said, "Here is how the equipment behaves in the field, and this is why." We have shown how to do simple technical calculations. The guiding idea of our book is that it is better to have a working knowledge of a few simple ideas than a superficial knowledge of many complex theoretical subjects.

The original three-day troubleshooting seminar has now grown into a six-day course that only covers about 50 percent of the subjects I tackled in the three-day class. Why? Because it is no longer primarily a troubleshooting seminar. The vast majority of the class time is now devoted to explaining how the equipment really functions and answering the following sorts of questions:

- Why do trays weep?
- Why do weeping trays have a low tray efficiency?
- What does tray efficiency actually mean anyway?
- Is there a way to design trays that do not weep?
- Why should an operator need to know why trays weep?
- Can a tray weep, even though the computer calculation says the tray cannot weep?

Several years ago I began to make notes of the questions most frequently asked by my clients and students. Sometimes, it seems as if I have been asked and have responded to every conceivable process equipment question that could possibly be asked. Certainly, I have had plenty of practice in forming my answers, so that they are comprehensible to most process personnel, maintenance people, and even management. We have tried to summarize these questions and answers in this book.

Like everybody else, I have answered questions without always being correct. But over the years, I have continued to learn. I have been taught by the source of all wisdom and knowledge—the process equipment itself. I am still learning. So you could say that this book is a progress report of what I have learned so far. I think that my troubleshooting field work and revamp designs have acted as a filter. This filter has removed, and still is removing, from my store of knowledge misconceptions as to the true nature of process equipment functions.

You do not need a technical degree to read and understand this text. Certainly this is a technical book. But the math and science discussed is high school math and science. We have traded precision for simplicity in crafting this book.

Liz and I would be happy to discuss any questions you might have pertaining to the process equipment discussed in our book. You can phone or fax us in the United States at:

Phone: (504) 887-7714

FAX: (504) 456-1835

But if you call us with a question, my first response is likely to be, "Have you looked the problem over in the field?"

Norman P. Lieberman
Email: norm@lieberman-eng.com

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Acknowledgments

Fortunately for us there are those who benevolently accept that students, just like children, are always with you.

The authors gratefully acknowledge the most kind and generous support of J. F. Richardson (JFR), in the production of the second edition, and also the timely assistance provided by R. P. Chhabra (Raj), J. Hearle (Jonathan), and J. R. Condor. The areas of this book dealing with fluid flow in pipes and hazardous pipe work would have been impoverished without their help and guidance.

My days at the University College Swansea (South Wales, UK), both during undergraduate years and at times since then when I have had the need or opportunity to revisit, are very special to me. The college and its staff have provided a rock-steady foundation for everything that comes my way as an itinerant Chemical Engineer alongside my coauthor Norman.

I will never forget the experience of working (quite literally) in the field with JFR, Raj, and Jonathan: sometimes paddling through inches of china clay slurry in an isolated pump house, or tracking down vent valves for pressure readings on a cross-country pipeline that traversed several miles in the heart of Cornwall (UK).

That hands-on training and field work, just as it should be, was very much part of the academic work of the thriving Chemical Engineering Department at the University College Swansea. We have to thank late Prof. J. F. Richardson for that, and we hope that his concept will live on and grow as a model to us all in his absence.

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CHAPTER 1

Process Equipment Fundamentals

I couldn't help but notice that the blue fish was permanently dead. Most sadly, it was floating on its side. The cause of death was clear. The water circulation through the aquarium filter had slowed to a thin trickle. Both the red and silvery striped fish also appeared ill. I cleaned the filter, but the water flow failed to increase.

As you can see from Fig. 1.1, the filter is elevated above the water level in the fish tank. Water is lifted up, out of the tank, and into the elevated filter. Water flowing up through the riser tube is filtered, and then the clean water flows back into the aquarium.

I tried increasing the air flow just a bit to the riser tube. The water began to gurgle and gush happily through the filter. Encouraged, I increased the air flow a little more, and the gush diminished back to a sad trickle.

It was too bad about the blue fish. It was too bad that I didn't understand about the air, or the filter, or the water flow. It was really bad because I have a master's degree in chemical engineering. It was bad because I was the technical manager of the process division of the Good Hope Refinery in Louisiana. Mostly, it was bad because I had been designing process equipment for 16 years, and didn't understand how water circulated through my son's aquarium.

Maybe they had taught this at my university, and I had been absent the day the subject was covered? Actually, it wouldn't have mattered. Absent or present, it would be the same. If Professor Peterson had covered the subject, I would not have understood it, or I would have forgotten it, or both. After all, "Universities are great storehouses of knowledge. Freshmen enter the university knowing a little, and leave knowing nothing. Thus, knowledge remains behind and accumulates."

But then I realized that I had seen all this before. Six years before, in 1974, I had been the operating superintendent of a sulfuric acid regeneration plant in Texas City. Acid was lifted out of our mix tank by injecting nitrogen into the bottom of a 2-inch riser pipe. The shift operators called it an "air lift pump."

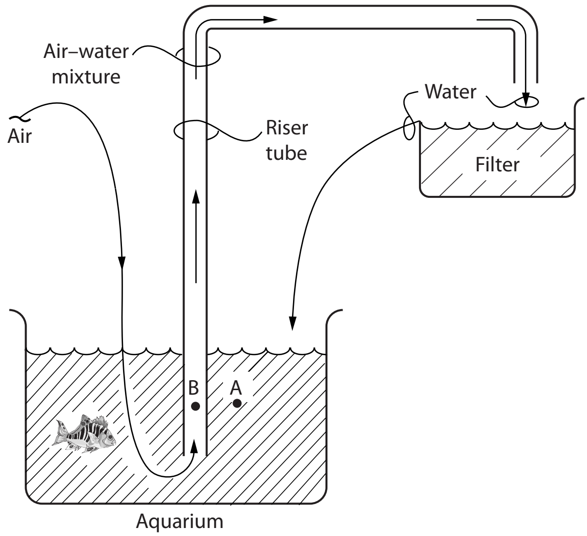

Figure 1.1 An air lift pump circulates water.

The problem was that in 1974 I didn't understand how the acid air lift pump worked either. More nitrogen pumped more acid. That's all we knew in Texas City, and all we cared to know.

Thinking about Texas City and my university days, my thoughts drifted to an earlier time. Back before my high school days in Brooklyn. Back to my childhood and to memories of my yellow balloon. The balloon was full of helium and I lost it. The balloon escaped because it was lighter than air. It floated up, up, and away because the helium inside the balloon was less dense than air. The yellow balloon was lifted into the sky because of the density difference between the low molecular weight helium inside the balloon, and the higher molecular weight of the surrounding sea of air.

So that's what makes an air lift pump work; density difference. Density difference between the lighter air–water mixture in the riser tube and the more dense water in the fish tank.

In Fig. 1.1, the pressure at point A will be greater than the pressure at point B. It's true that the height of liquid in the riser tube is triple the height of water in the tank. But because of the bubbles of air in the riser tube, the density of the mixed phase fluid in the riser is small compared to the density of water. The pressure difference between point A and point B is called the "airlift pump driving force." Water flows from an area of higher hydrostatic head pressure (at A) to an area of less hydrostatic head pressure (at B). Using more air reduces the density in the riser tube. This lowers the pressure at point B. The differential pressure between A and B increases.

The greater driving force then increases water flow through the aquarium's filter.

This still leaves a problem. Why did the second increment of air flow reduce the rate of water circulation?

1.1 Frictional Losses

We used to make wooden knives in Brooklyn, New York, by rubbing a stick on the sidewalk. The wood never got too sharp, but it did get hot. Sometimes it even smelled smoky when I rubbed the wood fast enough. More speed, more friction. Friction makes heat.

When the air–water mixture flows up through the riser tube, the potential energy (meaning the height of the circulating water) increases. The energy to supply this extra potential energy comes from the pressure difference between point A and point B. Some of the air lift pump driving force is converted into potential energy.

Unfortunately, some of the airlift pump driving force is also converted to frictional losses. The friction is caused by the speed of the air–water mixture racing up through the riser tube. More air means more flow and greater velocities, which means more friction. Too much air makes too much friction, which means less of the air lift pump driving force is left for increasing the potential energy of the water flowing up into the filter. At some point, increasing the air flow reduces water flow up the riser due to an increased riser tube pressure drop because of friction.

1.2 Density Difference Induces Flow

I'd better phone Professor Peterson to apologize. I just now remembered that we did learn about this concept that density difference between two columns of fluid causes flow. Professor Peterson taught us the idea in the context of draft in a fired heater. Cold combustion air flows through the burners and is heated by the burning fuel. The hot flue gas flows up the stack. The difference in density between the less dense hot flue gas and the more dense cold air creates a pressure imbalance called draft. Just like the fish tank story.

However, I can't call Professor Peterson. He's dead. I wouldn't call him anyway. I know what he would say: "Lieberman, the analogy between the air lift pump and draft in a fired heater is obvious to the perceptive mind, which apparently excludes you."

1.3 Natural Thermosyphon Circulation

I worked as a process design engineer for Amoco Oil in Chicago until 1980. Likely, I designed about 50 distillation columns, 90 percent of which had horizontal, natural thermosyphon circulation reboilers.

I saw hundreds of such reboilers in Amoco's many refineries. I never stopped to think what caused the liquid to circulate through the reboilers. I never thought about it, even though the reboiler feed nozzle on the tower was below the vapor return nozzle. Now, with my fish tank experience as a guide, I was able to understand:

- The reboiler shell is like the fish tank.
- The reboiler vapor is like the air.
- The reboiler return pipe is like the riser tube.
- The distillation tower is like the filter.

Every Saturday I run for 6 miles along the levee bordering the Mississippi River in New Orleans. Huge sand hills lie between the levee and the river. The sand has been dredged from the river bed by the Army Corps of Engineers. The Corps uses 30-inch diameter flexible hoses to suck the sand from the river bed. Maybe the concept of "sand sucking" is not the most elegant terminology? To be precise, a barge floating on the river, equipped with an air compressor, discharges air to the bottom of the 30-inch hose, 140 ft below the surface. The reduced density inside the hose, due to the compressed air, creates an area of low pressure at the bottom of the hose. The water and sand are then drawn into the area of low pressure and up the hose, which empties the sand and water into a basin along the riverbank. You can see a geyser of water and sand spurting up in these sand basins. I made a mini-dredge like that to suck the sand out of my pool sand filter. It worked rather well, until the little air compressor motor began smoking.

1.4 Reducing Hydrocarbon Partial Pressure

One day my mother served me a bowl of mushroom soup which I didn't want to eat. I disliked mushroom soup, but I was a practical child. It would serve no purpose to tell my mother I hated the taste of mushrooms because she would say, "I've spent all day cooking. You're not going outside till you eat that soup." So I said, "Mom, the soup is too hot. I'll burn my tongue." And she said, "Norman, blow across the soup to cool it off." While I knew this would cool the soup, I really didn't like mushrooms. So I responded, "Mom, why will blowing across the soup cool it off? How does that work?"

At this point your typical mother would slap the kid in the head and say, "Children in Europe are starving (this was in 1947; now European children are overweight). Shut up and eat your soup." But not my mother. "Norman, blowing across the soup blows away the molecules of steam covering the top of the soup. This makes room for more molecules of water to escape from the surface of the soup in the form of steam. When the molecules of water are changed into molecules of steam, that takes a lot of heat. This heat is called latent heat. This latent heat does not come from your breath, which is colder than the soup. The heat to vaporize the soup comes from the hot soup itself. The temperature of the soup is called sensible heat. When you blow across the soup, you're helping the sensible heat content of the soup to be converted to latent heat of evaporation of the soup. And that's why the soup cools. But your breath simply acts as a carrier—to carry away the molecules of steam covering the surface of the soup."

And I said, "What?"

And Mom said, "Norman, in effect, your breath is reducing the partial pressure of steam in contact with the soup. For every one weight percent of evaporation, the soup will cool by 10°F."

If my mother had served me a hydrocarbon soup, then for every one weight percent of evaporation, the soup would have cooled by 2°F. Then she would have said the carrier gas or stripping steam would be reducing the hydrocarbon partial pressure.

I have designed process equipment where the carrier medium is the air. Sometimes we use nitrogen or hydrogen. But mainly we use steam because it's cheap and condensable. We use steam:

- in the feed to towers.
- as the stripping medium in steam strippers.
- in evaporators.

The steam is used to promote vaporization of the product. But the heat of vaporization does not come from the steam, it comes mainly from the product itself. This is true even if the steam is superheated.

As an adult, I grow my own mushrooms on logs and consume them quite happily. Mom's gone now, and I would give a lot for a bowl of her mushroom soup. But I still remember the lesson about the reduction in partial pressure and the conversion of sensible heat to latent heat.

1.5 Corrosion at Home

My mother always thought that I was a genius. She would tell all the other mothers in our neighborhood, "You should have your daughter meet my son, he's a genius." My mother decided that I was a genius based on one incident that happened when I was six years old. She called me into the bathroom. "Norman! Look at the sink." The sink was discolored by brown, rusty stains from the old pipes in our ancient apartment house.

"Mom, I think my sister did that. It's not my fault. It's Arlene's fault."

"Norman, no one is blaming you for the stains. Stop blaming Arlene. What I want is for you to get the stains off."

So I went into the kitchen, got a bottle of Coke, poured it over the stains, and the sink became clean. From this single incident, my mother decided I was a genius and that all the teenage girls in south Brooklyn should fall in love with me. Actually, I went out with one of those girls—Gloria Harris. I really liked her. But she dumped me. Gloria told her mother that I was just another nerd.

What was it about the Coke that removed the iron deposits from our sink? It was carbonic acid (H_2CO_3). (Coke contains lots of phosphoric and citric acid too.)

Carbonic acid is formed when CO_2 dissolves under pressure in water. The resulting acid has a 5 to 6 pH, even at relatively high acidic concentrations. The acid readily dissolves iron to form water-soluble iron carbonate, $Fe(HCO_3)$.

This is a problem in process plant steam heaters. There are always some residual carbonates in boiler feed water. When the water is turned into steam, some of these carbonates decompose into CO_2. Thus, all steam is contaminated with CO_2. The CO_2 being far more volatile than water gets trapped and accumulates in the high points of steam heaters. With time, the CO_2 condenses in the water to form carbonic acid. This causes corrosion and tube leaks. To avoid CO_2 accumulation, the exchanger high points can be vented.

I knew all this when I was a child. Not the carbonic acid part. I knew that Coke dissolved rust stains from sinks. I had seen Mrs. Fredirico, my friend Armand's mother, clean a sink with Coke so I knew it would work. That's my idea of applied technology—applying the experiences of ordinary life to process problems. I tried to explain this to Gloria, but we were both teenagers and she wasn't interested. If she knew how much money I've made from my childhood experiments, I bet she would be sorry now.

1.6 What I Know

Sometimes I work with process equipment as a field troubleshooter. Sometimes I specify equipment as a process design engineer. And often, I teach shift operators and plant engineers how equipment works. Whatever I'm doing, I have in mind my childhood experiences in south Brooklyn. I focus on the analogy between the complex problem of today and the simple experiences of everyday life.

I often have my head in the clouds, but I always keep my feet on the ground. I learned this from my mother. She was a great storehouse of knowledge. And I've continued to learn as an adult too. Let me explain.

1.6.1 Toilet Training

The first skill that a new homeowner should acquire is toilet repair. I had my first lesson on this vital skill in 1969. We had just moved into our first house in south Chicago when I discovered our toilet wouldn't flush. An experienced co-worker at the American Oil Refinery in Whiting, Indiana (now BP), suggested that I check the roof vent (see Fig. 1.2).

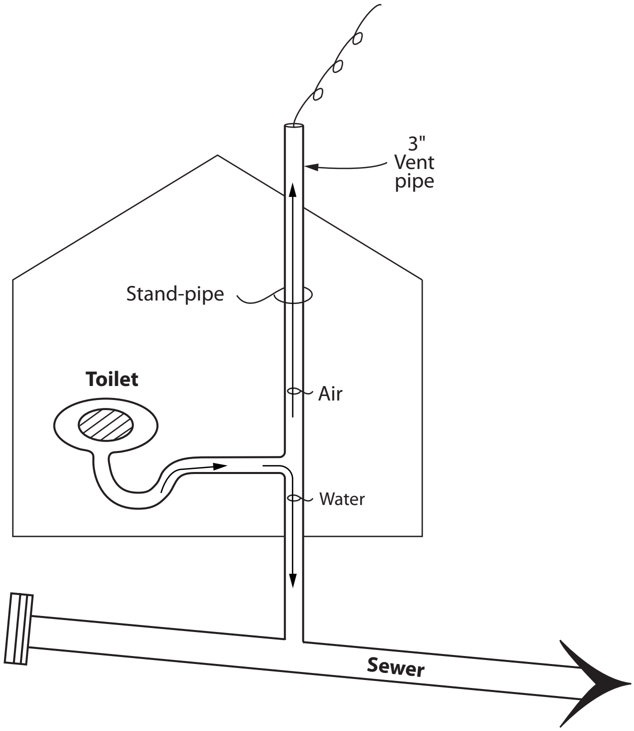

FIGURE 1.2 My toilet roof vent.

Climbing onto the roof I found that a pigeon had built its nest on top of the 3-inch diameter vent pipe. I removed the nest and the toilet flushed just fine. The water swirled around merrily in the bowl for a few seconds. Next, the water gushed and rushed down the toilet's drain with wonderful speed and vitality. The water seemed to be in such a hurry to leave the toilet bowl and escape through the sewer that it dragged a small amount of air with it.

The verb "to drag" is a poor engineering term. The correct technical terminology describing this well-known phenomenon is that the rushing water sucked the air down the toilet's drain. But the sucking of air out of my bathroom could only happen if the pressure in the toilet's drain was less than the pressure in my bathroom. This idea bothered me for two reasons:

1. What caused a sub-atmospheric pressure (a partial vacuum) to develop at the bottom of my toilet bowl?
2. Where did the air sucked down into the drain go to?

Here's the way it seems to me: When we flush the toilet, the velocity or the kinetic energy of the water swirling down the bowl increases.

The source of this kinetic energy is the height of water in the water closet. That is the potential energy of the water. We're converting potential energy to kinetic energy in accord with Bernoulli's equation.

If you live in an apartment house in Brooklyn, there is no water closet. The water supply for the toilet comes directly from the high pressure water supply line. Then we are converting the water's pressure to the velocity of water rushing into the toilet bowl. Either way, the spinning, draining water develops so much kinetic energy that the pressure of the water falls below atmospheric pressure. A slight vacuum is formed, which draws a small amount of air down the toilet's drain.

When the air–water mixture enters the larger, vertical stand-pipe in Fig. 1.2, the velocity of the air–water mixture goes down. Some of this reduced kinetic energy is converted back into pressure. This I know because the pressure in the stand-pipe is atmospheric pressure. This has to be because the top of the stand-pipe is the 3-inch vent pipe sitting on the roof of my house. The air sucked down the toilet bowl escapes through this 3-inch vent. If a bird's nest or snow clogs the vent, then the trapped air builds pressure in the stand-pipe. The back-pressure from the stand-pipe restricts the flow of water from the bowl, and the toilet can no longer flush properly.

This is an example of Bernoulli's equation in action. A steam vacuum ejector (jet) works in the same way. Centrifugal pumps and centrifugal compressors also work by converting velocity to pressure. Steam turbines convert the steam's pressure and enthalpy to velocity, and then the high velocity steam is converted into work, or electricity. The pressure drop we measure across a flow orifice plate is caused by the increase of the kinetic energy of the flowing fluid as it rushes (or accelerates) through the hole in the orifice plate.

Over the years I've purchased bigger and better homes. Now, Liz and I live in a house with seven bathrooms. Which is good, because at any given time, I almost always have at least one toilet mostly fully operational. Friends have asked why only two people need a house with seven bathrooms. Liz explains to them that, "If you ever tried to get my husband to fix anything, you would understand why Norm and I need a minimum of seven toilets in our home."

1.7 Distillation: The First Application

Extensive research has revealed that the best method to combat stress is alcohol. In 1980 I tried to become an alcoholic. Regrettably, I would fall asleep after my second drink. Ever since, I've had a desire to learn more about bourbon and scotch. In particular, in the production of a single malt scotch, how is the liquor separated from the barley mash?

Since 2003, I've been providing periodic process engineering services to a refinery in Lithuania. One evening after work, I was walking past the local village liquor store. Displayed in the window,

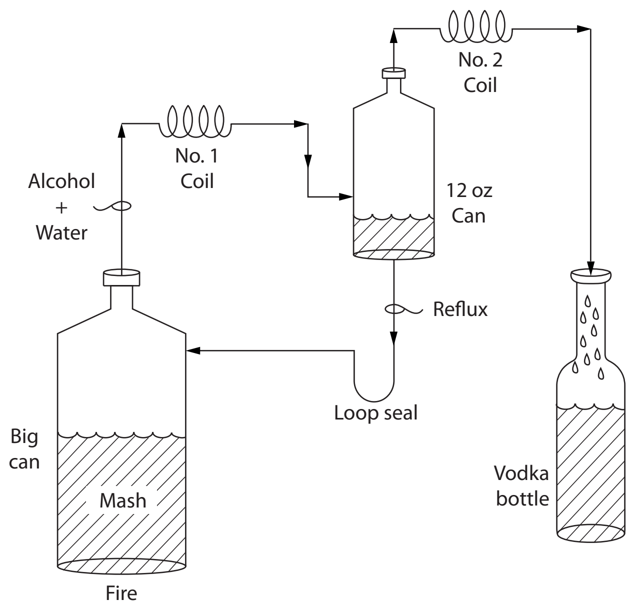

FIGURE 1.3 Vodka still: Lithuania, 2003. Device to separate alcohol from water.

surrounded by bottles of vodka, was a homemade still, as shown in Fig. 1.3. The two pots were just old soup cans. The big can containing the mash was about a gallon. The smaller can was 12 ounces. The appearance of the still suggested long use under adverse conditions. I'll provide a process description of this archaic apparatus.

The liquor in the big can is heated by a fire. The contents of the big can are:

- Water
- Alcohol
- Bad-tasting impurities

The objective is to produce vodka in the bottle of not less than 100 proof (that's 50 volume percent alcohol). Suppose that the bottle contains 80 proof (40 volume percent) alcohol. What can be done to bring the vodka up to the 50 percent spec?

There is only one thing that is under our control to change. This is the amount of firewood burned to supply heat to the big can. Should we add more heat to the big can or less heat?

If we add less heat to the big can, the vapor flow to the No. 1 condensing coil will diminish. As the water is less volatile than the alcohol, most of the reduction in vapor flow will be at the expense of water vaporization. Of course, there will be somewhat less vaporization of the more