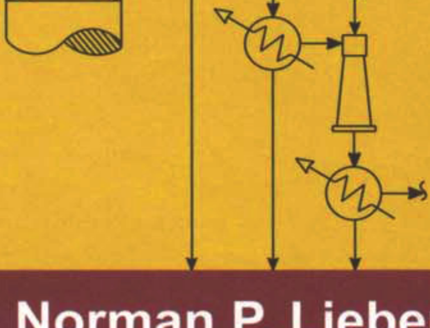
TROUBLESHOOTING VACUUM SYSTEMS

Steam Turbine Surface Condensers and Refinery Vacuum Towers



Norman P. Lieberman

WILEY

Scrivener Publishing

Troubleshooting Vacuum Systems

Scrivener Publishing
100 Cummings Center, Suite 541J
Beverly, MA 01915-6106

Publishers at Scrivener
Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)

Troubleshooting Vacuum Systems

Steam Turbine Surface Condensers and Refinery Vacuum Towers

Authored by

Norman P. Lieberman

Scrivener Publishing

WILEY

Co-published by John Wiley & Sons, Inc. Hoboken, New Jersey, and Scrivener Publishing LLC, Salem, Massachusetts.
Published simultaneously in Canada.

Cover design by Kris Hackerott

Cover image courtesy of Roy Williams

Library of Congress Cataloging-in-Publication Data:

ISBN 978-1-118-29034-7

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

To Liz – Wife, friend, and partner in life. She has climbed many a vacuum tower structure with me. Infrared temperature sensing gun in hand, Liz has provided innumerable surveys for steam ejector and inter-stage condenser surface temperatures for vacuum systems at the most remote corners and hostile environments of our little home planet.

Contents

Preface

Challenging Human Intellect

You might think that the author of a book pertaining to troubleshooting vacuum systems would be super successful in resolving such problems. Especially considering I've had 47 years of experience and practice on literally a thousand such systems, *and* considering that I am, at least in my own mind, really smart. But you would be very much mistaken.

I rarely resolve all the problems of vacuum systems on my first try. Often, I'll require several retrofit attempts to eliminate all the malfunctions. Not infrequently, I'll miss the point completely and only years later will someone else discover the underlying problem.

Process engineering is one of the most difficult activities that mankind has selected in our desire to dominate the universe. And, the performance of multi-stage ejector-condenser systems is clearly one of the most complex features of process engineering. The performance of such systems lies at the outer edge of average human comprehension. I guess that if one could engage the services of the very top intellects who have fanatically dedicated and devoted 100% of their time to vacuum systems, then surface condensers and vacuum towers could consistently be operated at design pressures.

But in reality, the vast majority of such systems are operated at some fraction of their design efficiency. Thus, there is, and will continue to be, a huge economic incentive in refineries, petrochemical plants, and power generation plants to correct vacuum system malfunctions.

So many of my clients operate with inefficient vacuum systems for so long, that they consider their current operations normal. They have no conception of the increased product yields or the energy savings that would result if they could only develop the design vacuum.

Often, I find my inability to identify a vacuum problem to be depressing. I'll be all alone, on the 8th landing, in the cold and damp of a dark night, listening to a great jet surging. The loneliness and isolation of the situation just makes me colder.

"Now what?!" I'll think. I'll be at the limit of my mental capacity to grasp the malfunction. But then, the defining characteristic of humankind comes to my aid. Not intelligence, but determination.

Need Help?

It is my intention in writing this book to contribute to the reader's ability to improve the performance of their vacuum systems. This has got to be a "Hand's-on" activity. However, often it may help you to discuss your observations with me. I never charge for such consultations. You can reach me at:

1-504-887-7714 (phone)
1-504-456-1835 (fax)
norm@lieberman-eng.com
www.lieberman-eng.com

Introduction

Time and Determination

Vacuum system malfunctions are treated in the process industry, and especially in my universe of petroleum refineries, differently than other sorts of process equipment malfunctions. Problems with pumps, compressors, fired heaters, and distillation towers are eventually resolved and corrected. Problems with vacuum systems are only too often never fixed or even recognized, meaning my clients just become accustomed to running with a bad vacuum.

A young engineer assigned to improve the vacuum in a lube oil asphalt, or a coker feed vacuum tower, will typically tread down the following path of frustration:

- Consult texts on vacuum equipment. Usually a waste of time. These texts describe how the vacuum equipment is supposed to work and not how it reacts to malfunctions such as wet steam, defective condenser seal strips, and eroded steam nozzles.
- Consult the equipment vendor. Totally a waste of time. These fellows do not understand how their jets react with the process itself and the associated equipment.
- Consult with a senior engineer. No help here. These gentlemen and ladies are always on their way to an important meeting and are too busy to work on such a humble task as ejector malfunctions.

So, the first step in troubleshooting ejectors and vacuum systems is to accept the fact that you'll have to do it by yourself. And how about reading my book that you've just purchased—the very text that you have in your hands right now? Well, if you will really read this book in its entirety, you will have a growing sense of desperation and depression. I know. I've been there a hundred times. It's all so terribly complex.

After all, if no one has solved this problem in the past 20 years, why would anyone expect you to resolve it? Perhaps it's best to make some superficial, long term recommendations and get on with your life. Here are a few such recommendations that you might suggest to your upper management and supervisors:

1. During the next unit turnaround, disassemble the ejector and ship the internals back to the manufacturer for testing.
2. Install a knock-out drum to provide dryer motive steam.
3. Purchase an on-stream analyzer to monitor the seal drum off-gas composition.
4. Re-tube the surface condenser bundle with 12 gauge Titanium tubes.

I'm often tempted to slip away from reality with these sorts of suggestions. But in my heart and soul, I know what's really required—steely determination. If I make enough field measurements, spend countless hours talking to the operators on all the shifts, run tests at various vapor loads, steam conditions, and cooling water flows, examine all the operating data and devote hours and days analyzing the problem, eventually I'll come to a profound conclusion. Which is then typically proven wrong by a definitive plant test. And then I'll have to start all over again.

It's that very willingness to discard all my theories and begin anew, with an open mind that is the key to troubleshooting vacuum systems. I must never give up. Better death than defeat.

However, to be entirely honest, sometimes I have given up and recommended to my clients that they replace an outmoded steam ejector with a modern model. Then, I'll look back on the project years and decades later with a feeling of sadness and longing for a squandered opportunity.

"If only I had lowered the boot level in the pre-condenser, perhaps I could have unloaded the primary ejector," I'll think. But it will be too late. That was 20 years ago in a refinery that still exists only in my memories.

Sometimes, I'll start out my troubleshooting assignment to improve vacuum performance, surrounded by an enthusiastic group of young tech service engineers, older operators, and supervisors—all watching and waiting for the famous expert to solve their vacuum system problem. Three days later, I'm sitting all alone on the stairs leading to the 5th landing of the vacuum tower. It's starting to rain, and the evening chill is settling down across the refinery.

Now what? I'm almost out of ideas. I've tried almost everything I know without success. But there's always one more concept to explore. Did I remember to check the motive steam pressure to the third stage jet? Maybe it's a lot lower than it's supposed to be. It's always that one final measurement or observation that leads to the correct solution and on to that ultimate victory.

You just have to have faith that the correct solution is within your grasp if only you try long enough and with sufficient fortitude.

As an old Stillman, Leroy Wilkes, once said to me in a Texas City refinery in 1974, "Son, it's only a matter of time and determination."

Definition of Terms

Air Baffle – Means the same as vapor baffle.

Air Equivalent – The capacity of a jet is expressed in pounds of air. Other vapors, depending on their molecular weight, are converted to their air equivalent.

Back-Flushing – Flowing cooling water backwards through a condenser tube bundle to remove fouling deposits.

Barometric Leg – Drains a vacuum condenser.

Break and Pick-Up Mode of Jet Operation – Same concept as jet surging or hunting (see below).

Compression Ratio – A jet discharge pressure divided by its suction pressure.

Condensate Backup – Poor drainage causes increases in condenser outlet temperature.

Converging Section – First part of the diffuser.

Cracked Gas – The vapor vented from the seal drum.

Critical Discharge Pressure – The maximum pressure at the jet outlet, above which the sonic boost is lost.

Critical Mode of Operation – The jet is developing its sonic boost.

Diffusor – Section of jet where the process gas is compressed.

Diffusor Throat – Narrow portion of diffusor between the converging and the diverging sections.

Diverging Section – Last part of diffuser.

Dry Vacuum Tower – Ejector is on top of the vacuum tower.

Ejector – Correct term for steam jet.

Final Condenser – Operates at atmospheric pressure. Vents to the seal drum.

Fixed Tube Sheet Bundle – The unfortunate, but widespread practice, of condenser construction that precludes shell-side bundle cleaning.

Flame Arrestor – Prevents flame propagating backwards from heater into seal drum.

Hardness Deposits – Silicates and carbonates that restrict steam flow in ejector steam nozzles.

Helium Testing – Standard industry method to locate air leaks.

Hot Well – The boot at the bottom of the condenser.

Hunting – The sound an ejector makes when it is surging.

Inter-Stage Pressure – The pressure between the discharge of a jet and the inlet to the following condenser.

Iso-Entropic Expansion – Describes the conversion of heat to kinetic energy in a steam nozzle.

Jet – A device that produces a vacuum. Properly called an Ejector.

Jet Breaking – The jet has suddenly lost its sonic boost.

Leaking Turbine Shaft Seal – Source of vapor load to ejectors in surface condensers (i.e., air).

Mixing Chamber – The section of the jet where the process gas mixes with the motive steam.

Motive Steam – The working fluid that is used to compress the process gas. Any high velocity fluid can also be used (water, diesel oil, natural gas).

Nozzle Erosion – Wet, high velocity motive steam will enlarge the I.D. of a steam nozzle.

Nozzle Freeze-Up – Moisture in motive steam has frozen in the steam nozzle.

Off-Gas – Same as cracked gas.

Penetration – Main specification used for paving asphalt. Varied by controlling vacuum usually by throttling on motive steam to ejector.

Pre-condenser – Heat exchanger on top of the vacuum tower.

Seal Drum – Used to seal the bottom end of the barometric drain legs.

Seal Strips – Thin metal strips used to seal the air baffle to the interior of the condenser shell.

Sonic Boost – Mechanism to compress process gas in converging section of diffuser by reaching critical conditions (i.e., the speed of sound).

Sonic Velocity – Speed of sound corrected for flowing density of gas.

Steam Nozzle – Part of jet where the motive steam enthalpy and pressure is converted to speed.

Sub-Cooling Baffles – Used in surface condensers to increase NPSH available to boot pump (i.e, Net positive suction pressure).

Surface Condenser – A shell and tube exchanger with water on the tube side and mostly steam vapors on the shell-side. Has both a liquid and vapor outlet.

Surge – Periodic loss of the Sonic Boost. Also called hunting.

Thermal Cracking – Gas evolution due to time and temperature.

Throttling Mode of Jet Operation – A jet that is operating with motive steam pressure being controlled to control vacuum at less than maximum.

Tube Support Baffles – Used in condensers to support cooling water tubes.

Vapor Baffle – Part of condenser tube bundle that reduces vapor outlet temperature (same as the air baffle).

Velocity Boost – Mechanism to compress process gas in diverging section of diffusor.

Velocity Steam – Used in vacuum heater to suppress cracked gas evolution.

Vendor Performance Curve – All jet systems should conform to the jet's operating curve.

Venturi Effect – Conversion of pressure to acceleration.

Wet Steam – Moisture in motive steam. Degrades jet performance.

Wet Vacuum Tower – Pre-condenser located on the top of the tower, upstream of the first stage ejector.

Other Books by Author

- *Troubleshooting Refinery Processes*
- *Troubleshooting Natural Gas Processing*
- *A Working Guide to Process Equipment* (with Elizabeth Lieberman) – 3rd edition
- *Process Design for Reliable Operations* – 2nd edition
- *Troubleshooting Process Plant Control (Wiley Publications)*
- *Process Engineering for a Small Planet (Wiley Publications)*
- *Process Equipment Malfunctions*
- *Troubleshooting Process Operations* – 4th edition

The best method to purchase any of the above texts is from 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

1

How Jets Work

No sane person is going to read this book unless they are troubleshooting vacuum system problems for steam turbine surface condensers or process vacuum towers. It's not a fun subject. As a matter of record, several of my closest colleagues have lapsed into insanity as a consequence of their interaction with ejectors, surface condensers, and seal drums.

I've never read a book, listened to a lecture, or seen a training video about vacuum systems. I have sometimes consulted vacuum system vendors, who have helped, but only up to a point. Still, my understanding as to how jets work is adequate for field troubleshooting.

1.1 The Converging-Diverging Ejector

A converging-diverging ejector is a two stage compressor, but with no moving parts. I've shown a sketch of such a jet

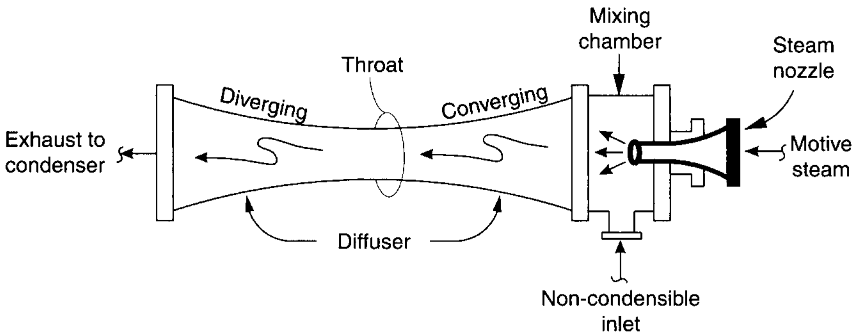


Figure 1.1 Components of a converging-diverging steam jet.

in Figure 1.1. If the jet has no moving parts, what is doing the work on the gas to compress it? The answer is the motive steam. And what property of the motive steam is doing the compression work? The answer is the velocity of the motive steam. This all has to be explained. It's rather complicated, but I'll make it simple for you.

You need to divide the ejector into three separate parts. I'll describe each part separately. Then, afterwards we can worry about their interaction.

- Part One – The Steam Nozzle – The steam nozzle is really small. You can probably hold a large one in your hand. It's much, much smaller in diameter than the steam supply line. It has a smooth, rounded opening. As steam expands through the steam nozzle, it accelerates from maybe 50 ft. per second in the supply line to perhaps 1,000 ft. per second at the discharge of the nozzle. The energy to accelerate the steam comes from two sources:
  1. Some from the pressure of the steam
  2. Most from the enthalpy (i.e., the heat of the steam)

I call the conversion of the steam pressure to kinetic energy, the Venturi Effect. This Venturi Effect is so efficient, that the pressure of the steam will drop as low as a few mm of Hg downstream of the nozzle in the mixing chamber (see Figure 1.1).

I call the conversion of the heat content of the steam to kinetic energy an Isoentropic Expansion. You can easily see what I mean. On your unit, check the temperature of the 150 psig (10 BAR) supply steam line. It's about 360°F (182°C). Now, check the temperature of the mixing chamber (which the nozzle exhausts into). It's about 90°F (assuming dry motive steam). What happened to the heat represented by the 270°F (360°F – 90°F) cooling of the steam? That heat was converted to speed. That's what Thermodynamics and the term, Isoentropic Expansion are all about:

- Thermo = Heat or Enthalpy
- Dynamics = Speed or Motion

- Part Two – The Converging Part of the Ejector – This is the half of the diffuser body that is downstream of the steam nozzle. It's perhaps 100 times larger than the steam nozzle. It's the front half of the diffuser shown in Figure 1.1. The motive steam enters the diffuser inlet at a velocity approaching sonic velocity or the speed of sound. The motive steam at this point already is combined with the off-gas from the vacuum tower or the upstream condenser vapor outlet. This off-gas has been drawn into the low pressure region of the mixing chamber created by the Venturi Effect of the motive steam.

  The narrowing cross-section of the converging section of the diffuser causes the motive