Heat Integration Complicates Heat Pump Troubleshooting

by

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Introduction

A naphtha fractionator unit had operated well for years but began to experience inexplicable warm weather trips of the heat pump compressor. During the summer the compressor would shut down on high discharge temperature for no apparent reason. Feed rates were high but not beyond design. The initial thought was that the compressor driver was inadequate. The compressor driver was due for overhaul – it would be an opportune time to replace it with a high Horsepower machine. Focusing on the compressor would be easy, and it might even be correct. However, you could also buy a large Horsepower driver, put it in, and have the same problem. That would be an uncomfortable look-back meeting. Perhaps that is why so few project look-back meetings are held...

The cost of a higher Horsepower driver was evaluated. It would be very expensive, but would be worth the expenditure if it worked. The unit outages during high product demand reduced production and raised maintenance costs. Before an order for a new compressor driver was placed though, a detailed review of the entire system was undertaken. Engineering is usually thought of as a cost. In this case, engineering was the best way to *reduce* costs. You could even conclude that engineering actually increased profits!

Heat Pumps

A heat pump adds mechanical work to a low value energy source so that it can be transferred to a high value energy sink. In the Hydrocarbon Processing Industry heat pumps are typically employed in condensing and reboiling fractionation columns. The traditional column of Figure 1 is shown as a heat pump design in Figure 2. The Figure 1 condenser and reboiler exchangers and their associated utilities are replaced by the compressor and single exchanger of Figure 2. The heat pump system uses the column's overhead duty for reboil. This is made possible by the compressor which boosts the overhead stream's pressure and temperature so that it condenses in the reboiler against the column bottoms.

Heat pumps derive their benefit from lower energy costs in comparison to traditional designs. The traditional design energy consumption is the sum of both the condensing and reboil duties while the heat pump energy consumption is only the compressor horsepower.

For a particular column, the economic viability of a heat pump versus a traditional design is determined to a great degree by the temperature difference between the column's top and bottoms. The larger the column temperature difference, the higher the required compression ratio and compressor horsepower. The ΔT sweet spot for heat pump applications is typically 20 to 40 degrees F. Low operating pressures that swell compressor size due to large volumetric flow rates, and high operating temperatures that push compressor design thermal constraints are two other conditions that exclude heat pumps from process consideration.

Heat pump systems are more complicated and typically require a higher initial capital outlay than traditional designs. Their elimination of heating and cooling utilities and their lower energy consumption must overcome this burden for a profitable application.

System

Figure 3 illustrates the system under review here. A naphtha stream is being fractionated to recover valuable products. The Depropanizer Bottoms is fed to the Debutanizer (DIB) of Figure 3 for C4's removal. The Debutanizer Overhead is sent to a Deisobutanizer where Isobutane is separated from *n*-Butane. The Debutanizer is a typical design and has the added benefit that its overhead is used in part to reboil the Deisobutanizer. The DIB with an overall column temperature difference of ~30 °F and an overhead pressure of ~70 psia is able to employ a heat pump for condensing and reboil.

Warm weather has the following effects at the plant:

- Compressor driver capacity diminishes.
- Cooling water temperatures rise.
- Air-cooler capacity decreases.

These factors conspired to induce repeated shutdowns of the DIB heat pump and the column it served during the summer. The outages were undesirable because of their negative effect on the unit and production, but also because they were unpredictable and recurring.

Compressor

The heat pump compressor was central to the investigation though its importance was diminished by later discoveries. Figure 4 is a sketch of the compressor with its minimum flow or surge control loop, also called a kickback. A flow meter on the compressor outlet opens the minimum flow loop if necessary to maintain compressor throughput above surge. Kickback loops often have a means to cool the compressor discharge thereby removing the heat of compression. If this is not done, as it is omitted in our case, the hot flow recycled to the compressor suction is heated to a higher temperature upon being compressed again by the machine. This quickly results in a compressor discharge temperature that threatens to damage the equipment. A high outlet temperature shutdown is in place to trip the machine for its protection. Every indication was that this sequence of events was causing the warm weather compressor trips. But what was causing the compressor flow to drop off?

The compressor driver is a gas turbine. Gas turbines lose Horsepower in warm weather as air density decreases with rising temperature. This can partially be offset with scrubbing the inlet air with water which cools and humidifies the air (evaporative coolers). Since the failures occurred during the heat of summer, a warm air related Horsepower loss could be a factor. However, after allowing for this effect the driver still should have been able to meet production rates. Something else had to be at work.

Gas turbines, simplified jet engines, wear and foul over time. Both mechanisms deteriorate the drive's capacity. Periodic water washing can restore part of the Horsepower lost to fouling, but over time unrecoverable losses buildup. The drive in this case was at its recommended overhaul point. Therefore it was known to be sub par when compared with design. These are real capacity losses that can be tracked over time and certainly an overhaul was due. But the question was whether or not to overhaul the existing driver or replace it with a larger one. Again, allowing for the effect of end-of-run deterioration, the compressor should not have been tripping off-line.

Hydraulics and Heat Exchange

As it leaves the compressor, the DIB overhead stream is now hot enough and at a high enough pressure to condense in the DIB reboiler. The compressor discharge is sent to the DIB Reboiler (E-1) where it condenses before entering the DIB Reflux Drum (V-1). The DIB Reboiler also receives heat from the Debutanizer Overhead. Employing the heat pump and two process heat sources to reboil the DIB provided excellent energy efficiency. Still, something was going awry in the summer.

The DIB reflux is cooled by an air-cooler and water cooler before it enters the column. Unfortunately, the water cooled exchanger had been out of service for some time due to tube leaks. This outage increased the compressor load approximately four percent versus it being in operation using hot summertime water. Together with the compressor driver capacity reductions due to hot air intake and end-of-run fouling, a case was building to explain the compressor trips. Certainly improving any or all of these items would upgrade compressor performance. But the accumulation of these constraints seemed to suggest a tower throughput limitation. They did not suggest the compressor would just unexpectedly shutdown.

A hint to the true cause of the problem came when an operator mentioned that the DIB reflux drum (V-1) PSV lifted intermittently during the summer. Normally the DIB Reflux Drum operated at a pressure comfortably away from its PSV set pressure. Since it was an equilibrium drum, its pressure was determined by the temperature and composition of the material within. If the upstream Depropanizer were slipping lights to the Debutanizer the DIB overhead composition would change and the DIB Reflux Drum would pressure up. But this problem was never seen. The DIB overhead Isobutane concentration was high and very steady. The temperature in the drum must be increasing to pressure up V-1.

What could cause the temperature in V-1 to rise? Some change in the DIB Reboiler was the only possible source of a substantial adjustment of the V-1 temperature. The Reboiler could be fouled, but it seemed unlikely as fouling was not something that would come and go with the sunshine. E-1 would be affected by a DIB bottoms composition change and by a DIB column pressure change. But neither of these things occurred. What was left then was the Debutanizer Overhead stream.

Both the Debutanizer Overhead and the DIB Overhead enter E-1 to supply heat to the DIB. A shift in reboiler heat duty from the DIB Overhead stream to the Debutanizer Overhead would warm V-1. Additionally it might prevent the DIB Overhead from fully condensing in E-1. This would lead to much higher pressure drops from E-1 to V-1. A composition change in the Debutanizer Overhead would result in a higher temperature that would affect E-1 operation. However, the culprit was identified as the Debutanizer pressure after walking past the Debutanizer Overhead Air-Cooler (E-2).

The Debutanizer Overhead Air-Cooler capacity had waned over the years. It was a large bank of coolers part of which had been taken out of service. Dirt and dust from the surrounding environment had fouled the fins. The old boy just wasn't what he used to be. Since there was adequate reboiler capacity, operations compensated for this by increasing the Debutanizer pressure in the summer. This worked very well. Debutanizer capacity was not impacted by warm weather. However, the deleterious effect on the DIB was not obvious. Increasing the column pressure at constant composition raises the overhead temperature. This increases the Debutanizer stream temperature driving force in E-1 thereby shifting duty away from the DIB Overhead. This resulted in two-phase flow from E-1 to V-1 and in higher temperatures in V-1. Both of these effects raised the required compressor discharge pressure.

Table 1 details necessary compressor discharge pressures for several scenarios. The Hot Weather case is deemed 'hypothetical' because it is really worse than shown in the table, though a compressor head 26% greater than design is bad enough. As soon as the process is unable to condense all the DIB Overhead Stream in E-1, vapor begins to travel to V-1. This vapor has no way of leaving the drum. Pressure builds until the PSV lifts – behavior noted by operations. At the same time the compressor must push against a higher and higher delivery pressure and rising two-phase frictional losses. This higher head requirement moves the compressor back on its curve until its flow drops off enough to activate the minimum flow loop. This recirculated flow leads to a high temperature discharge trip. It happens rapidly and with no apparent reason.

Figure 5 illustrates the vapor pressures of both column's overhead streams. These relationships define the importance of the E-1 heat balance. For example, a 10 °F increase in V-1 temperature results in a V-1 pressure increase of ~15 psi. That is 26% of the compressor design head. And moving the V-1 temperature ten degrees is not that hard. Increasing the Debutanizer pressure 10 psi increases its overhead temperature ~10 °F. Though not one for one, the Debutanizer Overhead temperature and the V-1 temperature are closely coupled. A seemingly small change in the Debutanizer pressure can easily overload the DIB compressor.

Slowly over time unit operation had deteriorated revealing a process complexity that was always there but not apparent. The Debutanizer overhead was shutting down the plant when its temperature rose in the summer. It is not unusual for equipment to degrade over time:

- Compressor driver at end-of-run cannot produce start-of-run Horsepower.
- Reflux water cooled exchanger out-of-service due to tube failures.
- Air-cooler fin fouling and partially out-of-service.

It also is not unusual to equate mitigation of these types of deficiencies with cost. Why fix these things? That just raises maintenance expenditures. In the end the choice was between spending a lot of money on a new compressor driver that might not do the job, and spending a little money on engineering that might turf up another answer.

After reviewing the findings, the plant decided not to install the costly upgraded compressor driver. Rather they overhauled the existing driver, and cleaned and maintained their exchanger systems. A new, larger compressor driver would have cost over ten times the cost of the engineering study and resulting maintenance – AND it would not have improved the operation at all. The plant is back running through the summer months still sweating with the warmth, but with equipment that can take the heat!

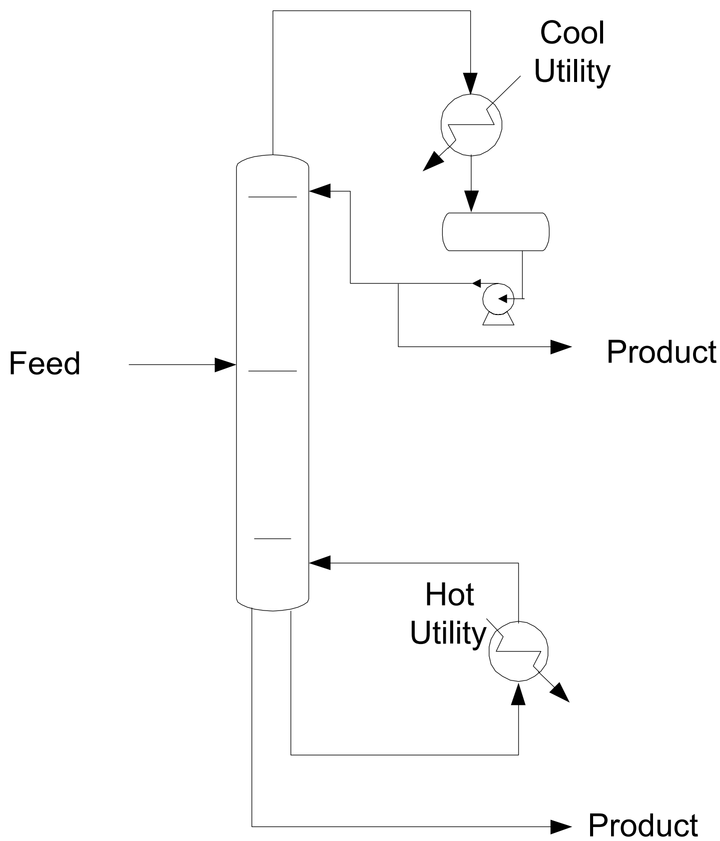

Figure 1 – Traditional Column

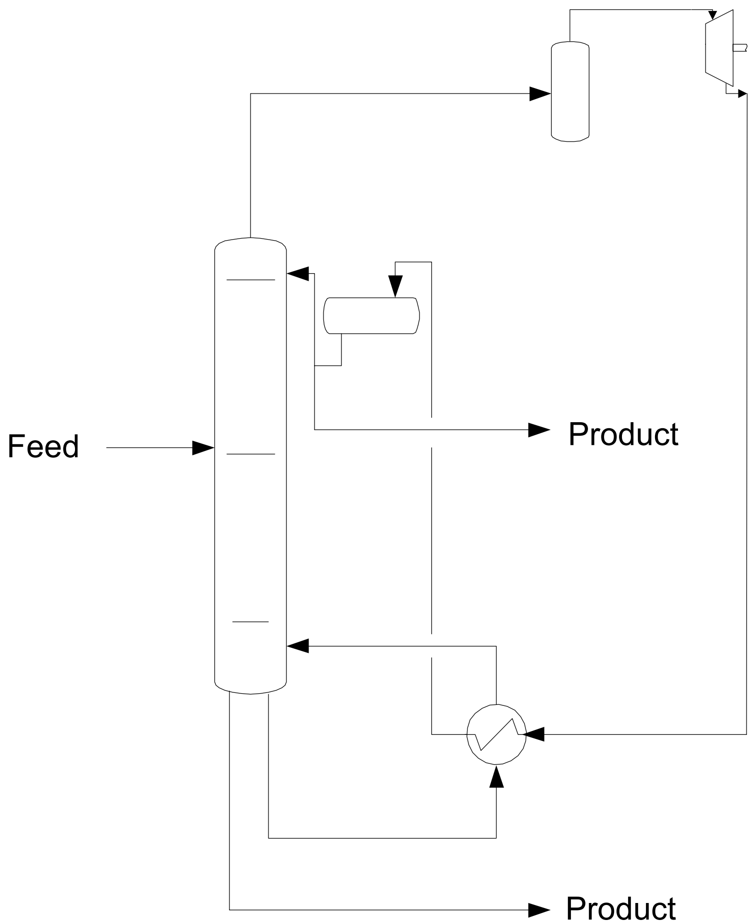

Figure 2 – Heat Pump Column

Table 1 – Required Compressor Outlet Pressure

Description	Original Design	Winter	Warm Weather	Hypothetical Hot Weather
Percent of Design Feed Rate	100	100	100	100
Required compressor pressure difference, psi	58	55	62	73
Compressor ΔP percent of design	100%	95%	107%	126%

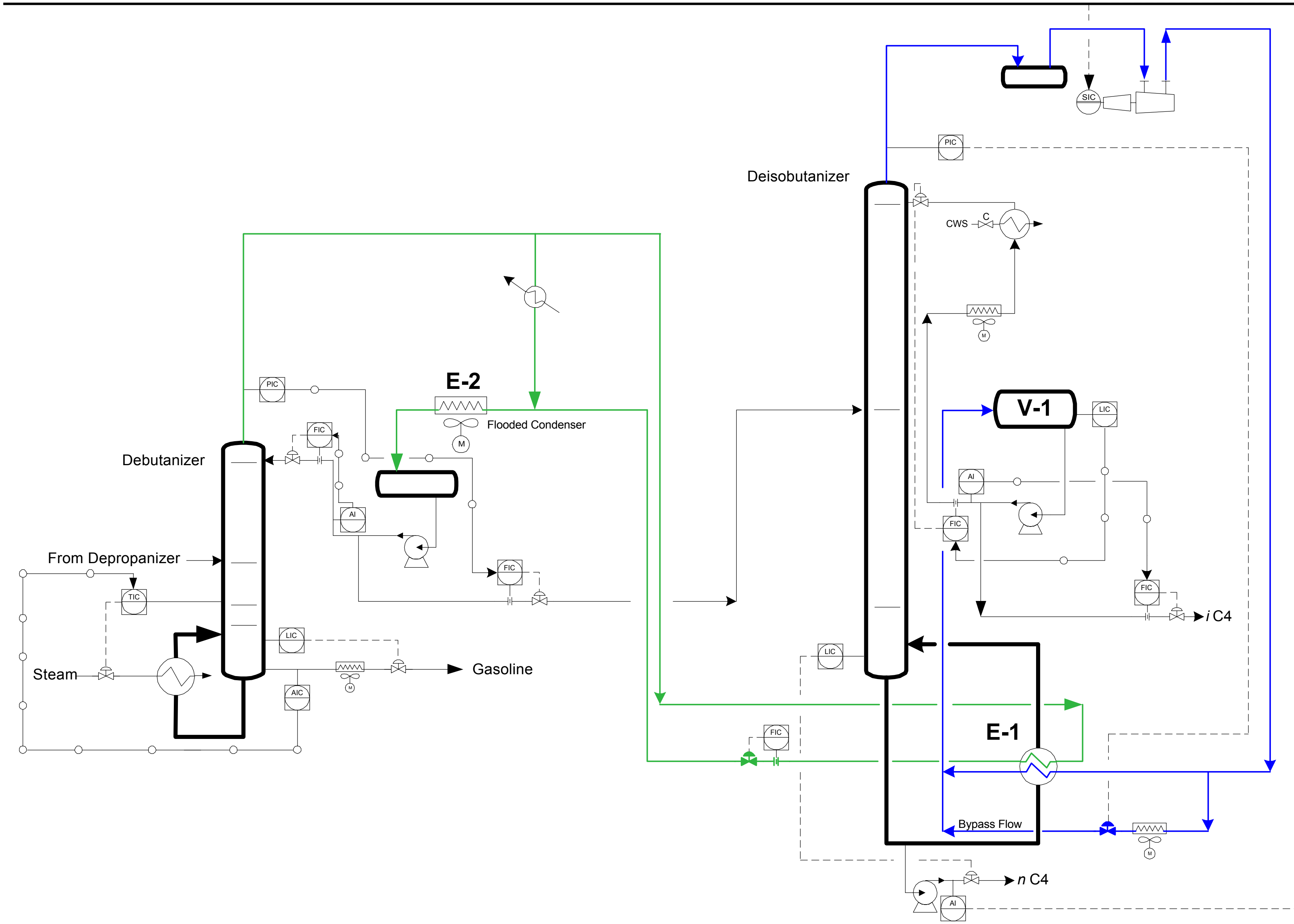

Figure 3 – System

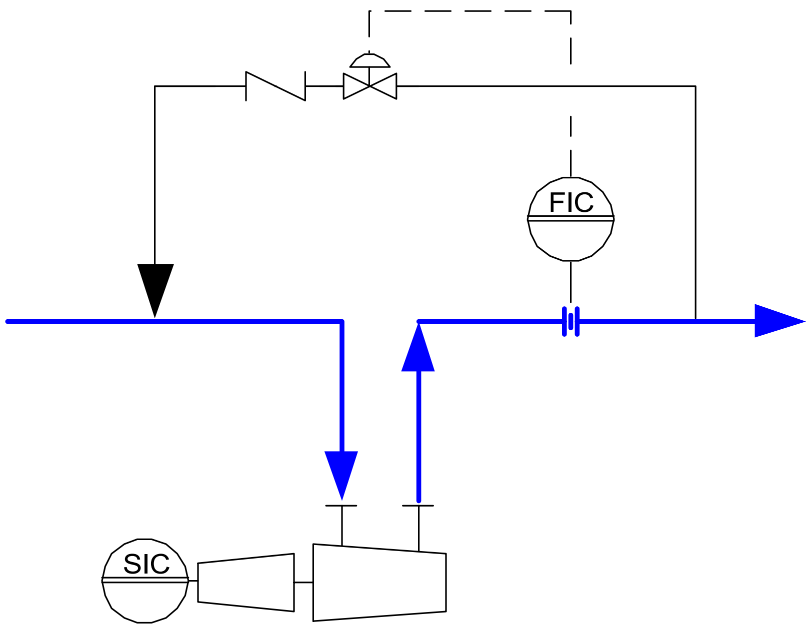

Figure 4 - Compressor

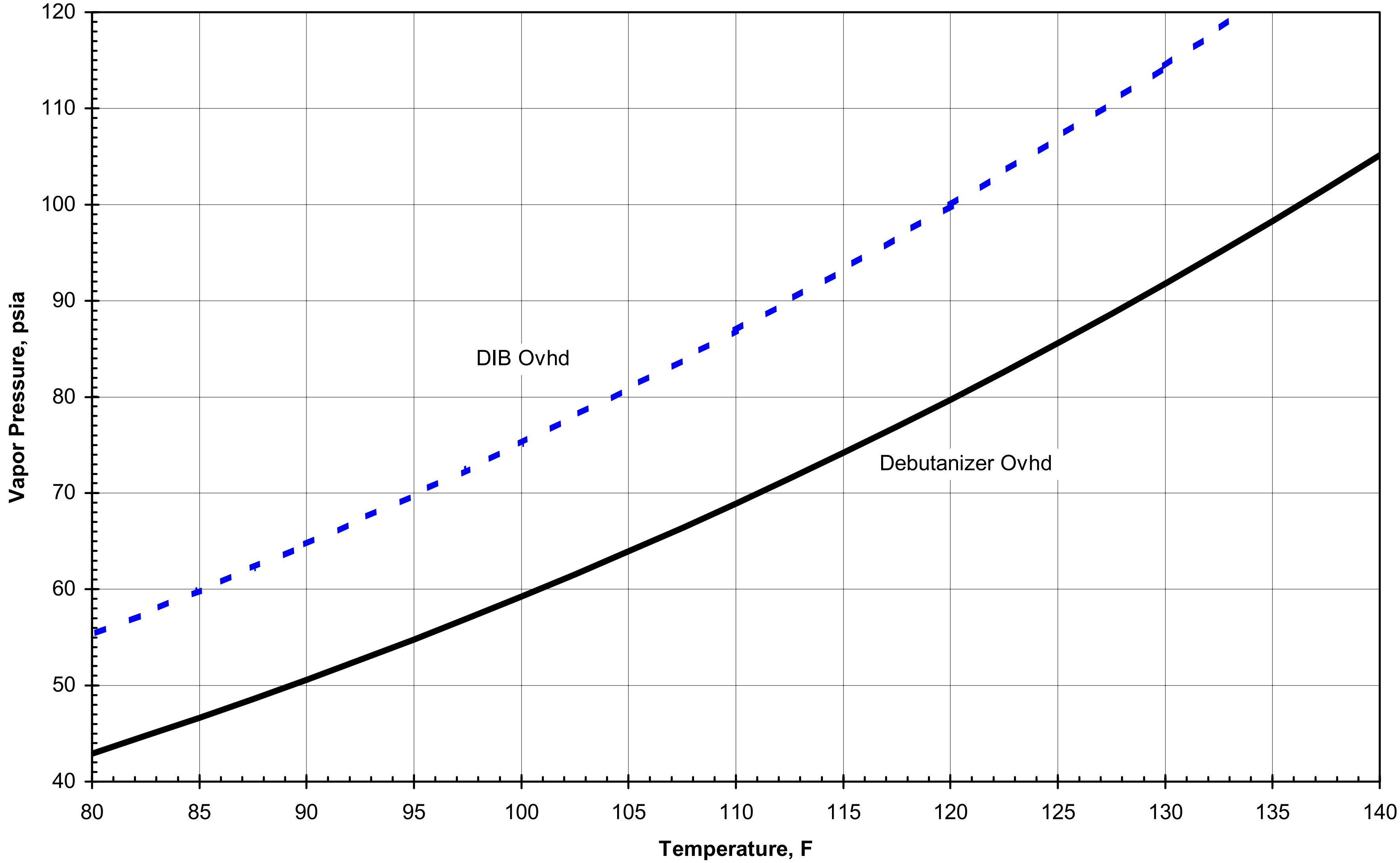

Figure 5 – Column overhead vapor pressures

Author Biography

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Don Schneider is President of Stratus Engineering, Inc., Houston, Texas. Previously he worked as a senior engineer for Stone & Webster Engineering, and as an operating and project engineer for Shell Oil Co. He holds a B.S. from the University of Missouri-Rolla, and an M.S. from Texas A&M University, both in chemical engineering. Don has authored or co-authored over a dozen technical papers and articles and is a registered professional engineer in Texas.

Author's Previous Publications

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