BG Pulse Journal USA
ISSN:1947-2536 http://www.bgpulseusa.com/index.php/bg
BG PULSE JOURNAL

ATMOSPHERIC AND VACUUM DISTILLATION IN CRUDE OIL REFINING: TECHNOLOGICAL SIGNIFICANCE AND PROCESS OPTIMIZATION

Bozorov Azamat
Chief Specialist of the Educational and Methodological Department at the Silk Road International University
azamatnazarovich1911@gmail.com
Doi: https://doi.org/10.5281/zenodo.21892035

Abstract: This article examines atmospheric and vacuum distillation as the principal separation stages in primary crude oil refining. The discussion covers crude preparation, heat recovery, furnace operation, fractionation, side stripping, vacuum generation, product routing, energy efficiency, process control, equipment reliability, industrial safety, and environmental management. Particular attention is paid to the relationship between crude properties and operating conditions, because density, sulfur content, salt concentration, water content, boiling-range distribution, and residue stability directly influence product quality and unit performance. The study uses a theoretical and technological analysis based on established refinery engineering literature. It concludes that stable product cut points, effective heat integration, minimized pressure drop, controlled residence time, corrosion prevention, and data-driven operation are essential for improving the efficiency and reliability of atmospheric-vacuum distillation complexes.

Keywords: crude oil, atmospheric distillation, vacuum distillation, fractionation, refinery, heat integration, vacuum gas oil, residue, process control, industrial safety.

Introduction

Crude oil is a highly complex liquid feedstock containing paraffinic, naphthenic, and aromatic hydrocarbons distributed over a broad molecular-weight and boiling-point range. It also contains sulfur, nitrogen, oxygen compounds, dissolved gases, water, inorganic salts, suspended solids, trace metals, resins, and asphaltenes. Because these components differ in volatility and thermal stability, the first task of a refinery is to divide crude oil into manageable fractions without causing excessive chemical conversion. Atmospheric and vacuum distillation perform this task and therefore determine the material balance, heat balance, and downstream feed quality of the entire refinery.Atmospheric distillation separates desalted crude into fuel gas, liquefied petroleum gas components, naphtha, kerosene, diesel-range material, atmospheric gas oil, and atmospheric residue. The separation is based primarily on differences in boiling behavior rather than on chemical reaction. However, the unit must operate within a narrow thermal window. If the furnace outlet temperature is too low, vaporization is insufficient and product overlap increases. If it is too high, cracking, coke formation, tube overheating, and unstable operation may occur. [1]

Vacuum distillation extends primary separation to the atmospheric residue. By reducing pressure, heavy hydrocarbons can be vaporized at lower temperatures, which limits thermal decomposition and permits recovery of light and heavy vacuum gas oils. These products are valuable feeds for fluid catalytic cracking, hydrocracking, lubricant production, and other upgrading processes. The non-volatile vacuum residue can be directed to bitumen production, visbreaking, delayed coking, solvent deasphalting, or residue hydroconversion.The purpose of this article is to explain the technological importance of atmospheric and vacuum distillation, identify the main operating variables, describe typical product routes, and outline practical measures for

improving energy efficiency, reliability, safety, and environmental performance. The paper does not report fabricated plant data; it presents an analytical synthesis of established refinery principles. [2]

Research Methodology

The article follows a theoretical-technological methodology. Standard petroleum refining textbooks, process design references, environmental guidance, and refinery operation literature were reviewed through content analysis and comparative analysis. The process was divided into functional blocks: feed preparation, preheat train, furnace, atmospheric column, side strippers, pumparound circuits, vacuum furnace, vacuum column, vacuum system, product recovery, and auxiliary environmental systems. Each block was evaluated according to its purpose, critical operating variables, common disturbances, and influence on downstream processing.The main evaluation criteria were product quality stability, energy consumption, pressure drop, furnace severity, vacuum depth, corrosion risk, fouling tendency, coke formation, equipment integrity, and suitability of recovered streams for subsequent conversion units. This approach provides a structured basis for understanding the atmospheric-vacuum complex as an integrated system rather than as two independent columns. [3]

Table 1.

Principal stages of an atmospheric-vacuum distillation complex

Stage	Primary function	Critical variables	Expected result
Desalting and dehydration	Remove water, mineral salts, and suspended solids	Temperature, wash-water rate, mixing intensity, electric field	Lower corrosion, fouling, and hydraulic instability
Crude preheat train	Recover heat from hot products and pumparound streams	Temperature approach, exchanger fouling, pressure drop	Reduced furnace fuel demand
Atmospheric furnace	Provide controlled vaporization before column entry	Coil outlet temperature, tube-skin temperature, excess oxygen, residence time	Adequate flash-zone vaporization without severe cracking
Atmospheric fractionation	Separate light and middle-distillate fractions	Column pressure, reflux, pumparound duty, stripping steam	Stable naphtha, kerosene, diesel, and gas-oil cuts
Vacuum furnace	Heat atmospheric residue under controlled severity	Outlet temperature, heat flux, flow distribution, residence time	Partial vaporization with limited coke formation
Vacuum fractionation	Recover vacuum gas oils from heavy residue	Absolute pressure, pressure drop, wash-zone operation, stripping steam	High-quality VGO and stable vacuum residue

Feed Preparation and Heat Recovery

Crude preparation begins with dehydration and desalting. Sodium, calcium, and magnesium chlorides may enter with formation water and can create corrosive species during heating. Water

also increases vapor load, disturbs furnace flow, and may cause column instability. Effective desalting therefore protects heat exchangers, furnace tubes, overhead systems, and downstream catalysts. Good performance depends on proper wash-water quality, mixing, emulsion breaking, temperature control, residence time, and electric-field strength.After desalting, crude passes through a heat-exchanger network where hot products and circulating streams transfer heat to the incoming feed. This heat integration is one of the largest energy-saving opportunities in the refinery. Nevertheless, exchanger fouling gradually reduces heat transfer, increases pressure drop, and raises furnace fuel consumption. Monitoring the thermal approach, overall heat-transfer coefficient, and pressure loss helps determine when cleaning or network reconfiguration is economically justified. [4]

Atmospheric Distillation Technology

The atmospheric furnace raises the crude temperature to the level required for partial vaporization in the flash zone. Furnace design and operation must provide uniform flow through parallel passes, stable burner performance, and sufficient heat transfer without excessive tube-wall temperature. Uneven flow distribution can create local overheating and coke deposits. Burner imbalance, poor atomization, inappropriate draft, and high excess oxygen reduce efficiency and may increase emissions. Continuous monitoring of coil outlet temperature, tube-skin temperature, bridgewall temperature, fuel pressure, and flue-gas oxygen is therefore essential.

When the heated crude enters the flash zone, the vapor phase rises and the liquid phase flows downward. On trays or packing, rising vapor and descending liquid approach equilibrium through repeated mass transfer. The top system condenses overhead vapor and provides reflux. Side draws are withdrawn at elevations corresponding to the desired boiling ranges. Side strippers remove lighter components from kerosene and diesel streams, improving flash point and product stability. Pumparound circuits withdraw hot liquid, cool it, and return it to the column, thereby controlling the internal heat profile while recovering useful heat for crude preheating or steam generation. [5]

The separation objective is not simply to maximize one product stream. It is to maintain stable cut points while respecting downstream constraints. Excessive overlap between naphtha and kerosene may burden hydrotreating and reforming. Heavy contamination of diesel can increase end point, density, sulfur, and smoke tendency. Excessively light atmospheric gas oil may reduce middle-distillate yield, while excessively heavy gas oil can carry metals, asphaltenes, and coke precursors into catalytic units. Product quality must therefore be controlled through coordinated adjustment of furnace severity, reflux, pumparound duty, side-draw rates, and stripping steam.

Table 2.

Main atmospheric and vacuum products and typical downstream destinations

Product stream	General characteristics	Typical downstream use	Key quality indicators
Fuel gas and light ends	Most volatile hydrocarbons and acid gases	Gas recovery, LPG treatment, refinery fuel system	Composition, H2S, pressure
Naphtha	Light liquid boiling-range fraction	Hydrotreating, reforming, isomerization	Boiling range, sulfur, density
Kerosene	Middle-distillate fraction	Jet-fuel or kerosene treatment	Flash point, smoke point, freezing behavior

Product stream	General characteristics	Typical downstream use	Key quality indicators
Diesel-range fraction	Heavier middle distillate	Diesel hydrotreating and blending	Cetane quality, sulfur, end point
Vacuum gas oil	Heavy distillate recovered under vacuum	FCC, hydrocracking, lubricant routes	Metals, CCR, sulfur, viscosity
Vacuum residue	Non-distilled bottom product	Bitumen, coking, visbreaking, residue upgrading	Asphaltenes, metals, viscosity, CCR

Product Quality and Cut-Point Control

Laboratory distillation curves, density, viscosity, sulfur, flash point, freezing point, carbon residue, and metal content are commonly used to evaluate product quality. Online analyzers can shorten response time, but laboratory verification remains important. The most effective control strategy combines temperature profiles, flow measurements, pressure data, inferential properties, and periodic laboratory results. A single temperature cannot fully represent product quality because crude composition and column hydraulics may change.

Vacuum Distillation and Heavy-Fraction Recovery

Atmospheric residue contains high-boiling hydrocarbons, resins, asphaltenes, sulfur compounds, nitrogen compounds, and trace metals. Heating this material at atmospheric pressure to the temperature required for further vaporization would cause severe thermal cracking. Vacuum distillation solves this problem by lowering the absolute pressure and therefore lowering the boiling temperatures of heavy components. The process recovers valuable distillates while limiting thermal degradation.The vacuum furnace is designed to minimize residence time and tube-wall temperature. High heat flux, low velocity, maldistribution, or excessive outlet temperature promotes coke formation. Coke narrows the flow area, raises pressure drop, worsens heat transfer, and can eventually lead to tube failure. Steam injection, balanced pass flow, controlled firing, and frequent monitoring of tube-skin temperature are common protective measures. Decoking schedules should be based on pressure-drop trends, heat-transfer deterioration, and inspection findings rather than on fixed time alone.

The vacuum column typically has a large diameter because vapor occupies a greater volume at low pressure. Internals are selected to minimize pressure drop. Structured packing, low-pressure-drop trays, wash sections, spray distributors, and carefully designed transfer lines help preserve vacuum depth. The wash zone captures entrained heavy droplets and protects vacuum gas oil quality. Inadequate washing can increase carbon residue, metals, and asphaltene contamination in the distillate, reducing catalyst life in downstream units.Vacuum is commonly produced by steam ejectors, surface or direct-contact condensers, liquid-ring systems, or combinations of these devices. Air leakage increases gas load, reduces vacuum, raises steam consumption, and may create flammable mixtures. Condenser performance depends on cooling-water temperature, fouling, and non-condensable-gas removal. Reliable vacuum operation therefore requires leak testing, ejector performance checks, condenser cleaning, and careful control of stripping steam. [6]

Table 3.

Key operating variables and their process effects

Variable	Main influence	Potential consequence of deviation	Primary control approach
Furnace outlet temperature	Determines feed vaporization	Low: poor separation; high: cracking and coke formation	Fuel firing, feed rate, pass balance
Column pressure	Defines boiling conditions and vapor density	Cut-point shift, capacity loss, off-spec products	Overhead condensation and gas removal
Reflux rate	Improves rectification and top-product control	Excessive energy use or hydraulic loading	Reflux flow and temperature control
Stripping steam	Reduces hydrocarbon partial pressure	High condenser load or poor stripping if misapplied	Steam-flow optimization
Vacuum depth	Enables heavy-component vaporization at lower temperature	Lower recovery and greater thermal severity	Ejectors, condensers, leak management
Wash-zone circulation	Limits entrainment into VGO	Metals and carbon-residue contamination	Wash-oil rate and distribution

Routing of Heavy Streams

Light and heavy vacuum gas oils are generally routed to catalytic cracking or hydrocracking, depending on sulfur, nitrogen, metals, carbon residue, and desired product slate. Vacuum residue may be sold as fuel or bitumen feed, but deeper conversion routes can increase the yield of transport fuels. Selection among visbreaking, coking, solvent deasphalting, residue hydrotreating, and hydroconversion depends on refinery configuration, hydrogen availability, crude quality, product demand, and environmental regulations.

Process Control and Energy Efficiency

Atmospheric-vacuum units are among the largest energy consumers in a refinery. Their efficiency is strongly influenced by heat integration. A well-designed preheat train recovers heat from atmospheric products, vacuum products, pumparound circuits, and residue streams. Pinch analysis can identify thermodynamic limitations and opportunities for network modification. However, theoretical heat recovery must be balanced against exchanger area, pressure drop, fouling tendency, maintenance accessibility, and operational flexibility.Furnace efficiency can be improved by controlling excess oxygen, maintaining burners, minimizing air infiltration, cleaning heat-transfer surfaces, recovering flue-gas heat, and optimizing stack temperature. Too little air causes incomplete combustion and carbon monoxide formation, whereas too much air carries heat out of the stack. Burner management systems, flame scanners, fuel-gas pressure control, and draft control are necessary for safe and efficient operation.

Advanced process control can coordinate furnace outlet temperature, column pressure, reflux, pumparound duties, side-draw rates, and product quality estimators. Model-predictive control is especially useful when crude properties change. It can reduce unnecessary energy use and stabilize product specifications by anticipating interactions that are difficult to manage through independent control loops. Nevertheless, advanced control only performs well when field instruments are

calibrated, analyzers are maintained, and operating constraints are correctly represented.Digital monitoring also supports fouling detection, predictive maintenance, and energy-performance tracking. Temperature approaches across exchangers, pressure-drop trends, furnace efficiency, steam use, cooling-water demand, and specific energy consumption can be visualized through performance dashboards. Data should be interpreted in the context of crude rate and crude quality; otherwise, apparent efficiency changes may simply reflect feed variation.

Reliability and Maintenance

Reliability depends on corrosion control, fouling management, vibration monitoring, rotating-equipment maintenance, and inspection of pressure equipment. Overhead corrosion is often associated with water, chloride-derived acids, hydrogen sulfide, ammonia, and deposit formation. Desalter performance, neutralizer and inhibitor programs, wash-water management, corrosion probes, thickness measurements, and inspection planning should be integrated. Poorly managed chemical treatment may merely shift the location of corrosion rather than eliminate it.Heat exchangers require attention to fouling, under-deposit corrosion, gasket integrity, and thermal stress. Pumps require reliable seals and appropriate minimum flow. Vacuum-system components must remain leak-tight. Furnace tubes require thickness monitoring, tube-skin-temperature surveillance, and inspection for bulging, oxidation, carburization, and coke deposits. Reliability programs are most effective when process data, inspection findings, maintenance history, and failure analysis are reviewed together. [7]

Industrial Safety and Environmental Considerations

Major hazards in atmospheric and vacuum distillation include high temperatures, large inventories of flammable hydrocarbons, pressurized equipment, hydrogen sulfide, furnace firing, vacuum-system air ingress, and loss of containment. Safe operation requires process hazard analysis, operating procedures, alarm management, interlocks, emergency shutdown systems, fire and gas detection, pressure relief, flare capacity, and trained personnel. Mechanical integrity must be maintained throughout the life cycle of the unit.Furnace hazards include flame failure, fuel accumulation, improper light-off, loss of flow, excessive tube temperature, and burner instability. Automated purge and ignition sequences, flame detection, low-flow trips, high-temperature trips, and operator verification reduce risk. A tube rupture can release hot hydrocarbons into the firebox and escalate rapidly, so early detection and emergency isolation are critical.Air ingress into the vacuum system can reduce performance and create a potentially flammable mixture. Leaks may occur at flanges, seals, instrument connections, manways, ejector systems, and condensers. Regular leak testing and maintenance are therefore required. Hydrogen sulfide exposure is another serious concern, particularly in overhead systems, sour-water streams, drains, and maintenance activities. Fixed detectors, portable monitors, respiratory protection, isolation, and permit-to-work procedures are essential controls.

Table 4.

Major hazards and preventive measures in distillation units

Hazard	Typical cause	Possible consequence	Preventive measures
Furnace tube coking or overheating	High heat flux, low flow, maldistribution	Tube rupture, fire, unplanned shutdown	Skin-temperature monitoring, flow control, decoking
Corrosion	Salts, HCl, H2S, water, deposits	Loss of containment and equipment	Desalting, chemical treatment, corrosion

Hazard	Typical cause	Possible consequence	Preventive measures
		damage	monitoring
Vacuum loss	Air leakage, condenser fouling, ejector malfunction	Lower recovery, higher furnace severity, instability	Leak testing, condenser cleaning, ejector checks
Hydrocarbon release	Seal, flange, valve, or tube failure	Fire, explosion, toxic exposure	Mechanical integrity, LDAR, gas detection, isolation
Off-spec product	Incorrect cut point or unstable hydraulics	Downstream catalyst or product-quality problems	Analyzer validation, coordinated control, lab confirmation
Sour-water release	Poor drainage or containment	Toxic exposure and water pollution	Closed drains, sour-water stripping, emergency response

Environmental management focuses on combustion emissions, fugitive volatile-organic-compound emissions, sour water, oily drains, slop systems, flare operation, and energy-related greenhouse-gas emissions. Leak detection and repair programs target valves, pump seals, flanges, and connectors. Closed drainage and vapor recovery reduce uncontrolled releases. Atmospheric overhead water may contain sulfides, ammonia, phenols, and hydrocarbons and should be sent to sour-water stripping and wastewater treatment rather than discharged directly.Reducing fuel consumption also reduces carbon dioxide emissions. Heat recovery, furnace optimization, steam-system management, fouling control, and flare-gas recovery can therefore improve both economic and environmental performance. Environmental improvement should be measured with consistent indicators such as specific fuel use, specific steam use, flare rate, wastewater load, and fugitive-emission findings.

Discussion

Atmospheric and vacuum distillation define the operating foundation of a refinery. Their influence extends far beyond primary separation because every downstream unit depends on stable feed composition. Poor naphtha cut control can disturb reforming and isomerization. Heavy contamination of middle distillates increases hydrotreating severity. Metals and carbon residue in vacuum gas oil shorten catalyst life in catalytic cracking and hydrocracking. Unstable residue quality complicates coking, bitumen production, and residue conversion. For this reason, the atmospheric-vacuum complex should be managed as a refinery-wide feed-conditioning system.Optimization must balance yield, quality, energy, capacity, reliability, and safety. Pushing furnace temperature for short-term yield may increase coking and maintenance. Increasing reflux may sharpen separation but raise energy demand and column loading. Increasing stripping steam may improve some cuts but burden condensers and the vacuum system. The best operating point is therefore constrained and dynamic. It changes with crude composition, product values, ambient conditions, equipment condition, and downstream availability.Modern operation increasingly combines first-principles understanding with online measurements, inferential models, and advanced control. Yet digital tools cannot compensate for poor field instrumentation, inadequate maintenance, or weak operating discipline. Sustainable improvement requires verified data,

competent personnel, clear procedures, and feedback between laboratory, operations, maintenance, process engineering, inspection, and environmental teams.

Conclusion

Atmospheric distillation separates crude oil into light and middle fractions, while vacuum distillation recovers heavy distillates from atmospheric residue at reduced pressure and limited thermal severity. Together, these processes determine the feed quality, energy demand, and operating stability of the refinery.High performance depends on effective crude desalting, efficient heat recovery, controlled furnace severity, stable column pressure, appropriate reflux and stripping steam, low pressure drop, reliable vacuum generation, good wash-zone operation, corrosion control, and timely maintenance. Product quality must be assessed through both process indicators and laboratory or online analytical data.Energy efficiency and environmental performance are closely connected. Better heat integration, cleaner exchangers, optimized burners, reduced steam waste, controlled flaring, closed drainage, and fugitive-emission management lower both operating cost and environmental impact. Safety remains a primary condition for all optimization activities.

Practical Recommendations

1. Maintain stable crude desalting and dehydration performance before furnace heating.
2. Track exchanger fouling and pressure drop to preserve preheat-train efficiency.
3. Monitor furnace tube-skin temperature, pass balance, and burner combustion continuously.
4. Control product cut points using coordinated temperature, flow, pressure, analyzer, and laboratory information.
5. Verify vacuum-system tightness and condenser-ejector performance on a planned basis.

References

1. Gary, J. H., Handwerk, G. E., and Kaiser, M. J. Petroleum Refining: Technology and Economics. 5th ed. CRC Press, 2007.
2. Speight, J. G. The Chemistry and Technology of Petroleum. 5th ed. CRC Press, 2014.
3. Fahim, M. A., Al-Sahhaf, T. A., and Elkilani, A. Fundamentals of Petroleum Refining. Elsevier, 2010.
4. Wauquier, J. P. Petroleum Refining, Vol. 1: Crude Oil, Petroleum Products, Process Flowsheets. Editions Technip, 1995.
5. Kaes, G. L. Refinery Process Modeling. Kaes Enterprises, 2000.
6. Towler, G., and Sinnott, R. Chemical Engineering Design. 2nd ed. Elsevier, 2013.

Kemp, I. C. Pinch Analysis and Process Integration. 2nd ed. Butterworth-Heinemann, 2007.