

ROBUST VACUUM SOLUTIONS IN BIOMASS PROCESSING

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ABSTRACT: The success in converting biomass feedstock to financially viable products is down to combining good ideas and optimising resources such as vacuum. Safety, pollution prevention and control, energy consumption, processing times, quality and yield in many applications in biomass processing, as in other industries, are influenced by vacuum equipment. Minimising capital and running costs and optimising throughputs are significant benefits. Correct sizing and selection of vacuum systems can contribute significantly to these benefits. The capacity of the vacuum system varies from a laboratory to a biorefinery but the same design data and selection rules apply. Sizing of the vacuum equipment, including piping and accessories, is determined from process parameters such as air leakage, pressure, temperature and vapour flows. Selection of the correct technology, (wet, dry or combinations), is the next step in the design. Wet technologies include liquid ring vacuum pumps, steam, ejectors and oil-sealed pumps. Dry technologies include claw, screw and Roots mechanisms and air ejectors. Correct system design is the concluding step in ensuring mechanical, electrical and regulations and standards such as PED, DIN, ATEX and IPPC are met. These lead to safe and reliable systems with environmentally friendly and economic end-products.

Keywords: vacuum technologies, biofuels, combined heat and power generation (CHP), air leakage.

1 INTRODUCTION

This paper discusses:

- The role of vacuum in biomass processes
- Vacuum and pressure applications in some biomass processes
- Vacuum equipment technologies, sizing, selection and system design and operation
- The need for different parties to co-corporate at each project stage to meet the overall project objectives which includes cost of ownership, safety and minimum environmental impact.

2 VACUUM IS MORE THAN JUST A UTILITY

Vacuum, or sub-atmospheric pressure, affects project economic justification since it influences utility consumption, processing times, quality, yield, safety and environmental impact. These factors also influence the size and type of vacuum equipment and hence cost of ownership. Operating at vacuum pressures allows processing at lower temperatures to optimize energy usage. Low temperatures also prevent adverse final colour effects and damage to heat-sensitive products. Vacuum also enhances product quality by removing impurities. Vacuum degassing of dissolved gases before further processing, e.g., before extrusion, evaporation and molecular distillation, is also sometimes required for sizing, operational and quality needs. Vacuum can be a primary requirement for ensuring safe operation by excluding oxygen. Operating at low pressures may also be a processing prerequisite as in the case of azeotrope splitting. Additionally, vacuum increases yield by shifting reaction equilibria. Vacuum is also sometimes used for product transfer. Pneumatic conveying, using either vacuum pumps or blowers, is another example of how low pressure (above and below atmospheric) is such a vital and versatile resource for the process industry.

Air leakage is a primary factor when sizing vacuum systems. Air leakage also affects exhaust emissions [1]. Unless limited, it also influences plant costs. Limiting air leak rates and optimizing manufacturing integrity levels for plant items early reduces vacuum equipment size or increases vacuum levels.

To illustrate the point, consider the following equation:

$$m_{\text{air}} = 0.07V \times \Delta P/\Delta t \quad (1)$$

where:

m_{air} = air leakage (kg h^{-1})

V = system volume (m^3)

$\Delta P/\Delta t$ = pressure rise with time (mbar/min)

= $(P_2 - P_1)/(t_2 - t_1)$

= 2 to 3 mbar/min for existing plants

= 0.75 to 1.5 mbar/min for new plants

NB:

1. Add a further 0.5 to 1 kg/hr air leakage for each agitator in a system

2. The American Heat Exchange Institute has developed standards and charts for air leakage into systems [6, 7]

P_2 = end pressure (mbar)

P_1 = starting pressure (mbar)

t_2 = end time corresponding to P_2 (min)

t_1 = the starting time corresponding to P_1 (min)

If $\Delta P/\Delta t$ is reduced from 2 mbar/min to 1 mbar/min through better manufacturing and installation integrity, the mass of air leaking into the system is reduced by 50%. The vacuum pump capacity is also reduced by 50% at a given temperature and pressure.

Limiting air leakage can also affect pollution since the higher the flow of non-condensables, the greater the exhaust emission from the vacuum system.

3 VACUUM IS NEEDED WHATEVER THE PROCESS STAGE OR PLANT SIZE

Whether it is a research establishment, pilot plant, medium to large process plant, or even a biorefinery, vacuum is required in many processes. The capacity of the vacuum equipment may be different but vital scale up data from laboratory to full scale production can be significant to plant optimisation and viability. Equally, vacuum can be found in all stages of processing from pre-treatment to final product manufacture. Again, capacity, (volumetric throughput in $\text{m}^3 \text{h}^{-1}$ or acfm, for example), and pressure, (in mbarA or TorrA, for example), varies from application to application but the same sizing rules and benefits apply.

Examples of process stages or process treatment plant requiring vacuum equipment are given later but whether it is low or high pressure generation, both are created using compressors. (Compressors discharge to a higher pressure than at the inlet). Dual cycle machines (exhausters) are also used in biomass processing. These operate with suction pressures below atmospheric and discharge pressures above in a single machine. The ability to operate this way or cycling between vacuum and pressures above atmospheric has been utilised for many years for extracting and boosting methane for both safety and energy generation, for example. Positive pressure compressors have been used on similar applications to those found in biomass processing for many years.

It is the low pressure applications that offer most benefits. For example, liquid or solid product transfer under vacuum is safer and can be more energy efficient. Loading a reactor with solids and liquids from different locations can be achieved more efficiently under vacuum when compared with positive pressure as only one source is required. Similarly, liquid transfer under vacuum is generally safer because any pipe fracture would cause air to leak in, not out. Compressed air and process material leaking out is potentially very dangerous.

Irrespective of plant size, three phases of processing biomass feedstock [2] are considered:

- pre-treatment
- conversion process and
- final product manufacture.

Pre-treatment of feedstock to remove impurities employs washing followed by filtration, drying and blending to enhance final product quality and easier processing. Vacuum can be used to improve feedstock purity through degassing, deodorization, drying or desorption.

Conversion plants handling dry or wet biomass feedstock employ similar processes to those found in the chemical and petrochemical industries. Whether the end product is a biofuel or another chemical, the benefits of reactors, distillation columns and evaporators operating under vacuum include reducing energy use, production times and costs. Vacuum or low pressure blowers can also be used to enhance viability through recovery or recycling as seen in tank farms, digesters, dryers or exhaust management systems. Table I contains other examples of vacuum and pressure applications and technologies in biomass processing.

Final product manufacture derived from biomass feedstock, eg., solvents, fuels, lubricants, organic acids

and plastics often use vacuum. Mature processes, such as wood pulp production and sugar refining, produce biomass feedstock as a by-product, using vacuum and pressure as primary utilities. Vacuum in sugar refining enhances final product quality and yield through evaporation, degassing and cleaning and boosting carbon dioxide for bleaching. Vacuum pumps and compressors are used in the pulp and paper industries for pulping, stock degassing, flow control, drying and final product conversion.

Another example is the extraction of landfill gas using exhausters and boosting gas for use in brick kilns or as a fuel for heating and or power generation. Experience using similar technology to extract and boost methane from deep coal mines is another example of how equipment suppliers cannot only refer to existing similar applications to determine the right pressure level, but also the correct technology to use on related biomass processes.

Solvent recovery or gas recycling, (e.g., filter dryers and sugar purification), use compressors operating at relatively low pressures. Being able to deliver clean gas maximises solvent recovery and enhances product quality. Exhaust condensers operating above atmospheric pressure increase condensing efficiency and vapour recovery and reduce exhaust emissions.

Recycling, product transfer, blending and mixing also benefit from the flexibility of correct equipment selection whatever the pressure regime. These include gas compression boosting digester gas, dual fuel engines and vacuum pumps aiding the steam cycle on a combined heat and power (CHP) plant turbine condenser set.

Biomass processing for transport and heating and power generation can be combined in a single plant, (Fig. 1). Bioethanol from biomass may involve cellulose hydrolysis, evaporation, fermentation, distillation and dehydration. The non-fermentable organics can be used as fuel for the CHP plant. Dehydrated ethanol can be used as transportation fuel. Ethanol dehydration typically uses vacuum in a pervaporation or molecular sieve process. Other chemicals, such as vinegar, esters, ethylamines can be derived from ethanol or it can be used directly as a solvent or antiseptic.

The efficiency of steam turbines is an important part of generating electricity. Steam is condensed, either by a water-cooled or and air-cooled condenser, after it leaves the turbine. Condensing the steam creates a vacuum inside the turbine exhaust condenser. To maintain this vacuum, air and other non-condensable gases that leak into and build up within the condenser must be extracted by vacuum pumps.

4 CO-OPERATION IS VITAL TO ACHIEVE THE COMMON OBJECTIVE

Many issues influence project justification and cost. Minimising air leakage is an excellent example of how to resolve a problem collectively. To the processor, air leakage affects pump size, vacuum levels, energy consumption, emissions, and capital and running costs. The plant supplier and installer, on the other hand, must ensure process equipment and all interconnecting piping are pressure and leak tested in line with agreed leakage limits, specifications and standards such as ASME, PED etc.

Capacity requirements, however, cannot be fully resolved until operating parameters, (e.g. mass balances, temperatures and pressures, etc.), are finalised. Therefore, only through co-operation can equipment selection be optimised to meet the overall project goals such as safety, throughput, environmental impact and profit.

5 VACUUM EQUIPMENT SIZING

Sizing of the vacuum equipment, including piping and accessories, is determined from process parameters such as air leakage, pressure, temperature and gas composition. Correct sizing ensures correct functionality and meeting processing objectives (quality, yield, cost, etc.). Eight main parameters affect the sizing of vacuum equipment, whatever the size of plant or process phase:

i. System volume

The plant or process line will have at least a process vessel and associated equipment such as condensers, collection vessels and inter-connecting pipework. The connection of these components to the vacuum system determines the “system volume”. System volume affects air leakage as it is directly proportional to volume as shown in eqn. (1).

ii. Air leakage

Air leakage can be controlled by manufacturing and pressure or leak testing components to meet the appropriate manufacturing and environmental regulations and standards. Equally important is installation integrity since the number of connections affects air leakage. Correct sealing of joints and leak testing is vital to leakage minimisation and control.

iii. Process temperatures

Process temperatures are determined at the basic engineering stage. Operating temperatures are driven by product characteristics such as heat sensitivity, colour, vapour pressure and energy requirements. Lower operating pressures reduce process temperatures. This leads to product as well as processing benefits such as higher production rates, yields and purities and lower energy consumption.

iv. Process pressures

One parameter that influences operating pressure is the vapour pressures of the process materials. Vapour pressures, air leakage, pipe pressure drop and vacuum system capacity limit the attainable vacuum.

v. Vapour composition & partial pressures

The existence of other permanent gases produced from the process or added, e.g., nitrogen for inerting, is important, since like air, they play a major part in vacuum pump sizing. Apart from the presence of permanent gases, most chemical processes involve liquids which evaporate and will influence final processing pressures. If condensed, their mass flow rates in the vapour phase are functions of their partial pressures. Miscible vapours exert partial pressures as a function of their mole fractions. Immiscible vapours exert their pure vapour pressures irrespective of their mole fractions.

The calculation of partial pressures can be

complicated and is not dealt with here [3, 4, 5]. The effect of condensable vapours on operating pressures can be significant and may dictate the optimum vacuum technology and system configuration.

vi. Mass flow rates

The total volumetric flow rate for pump sizing is calculated from the component mass flow rates using the ideal gas law. The required capacity and pressure helps to select the correct vacuum technology, (see Table II). The optimum selection depends on the best cost of ownership when all factors e.g. capital, running and maintenance costs, are accounted for.

vii. Pressure drop

Keeping system components and pipework dimensions and leak tightness to a minimum is one project goal. However, if the pipework is too restrictive, the required system pressure may be unattainable due to excessive pressure drop. To reduce pressure drops (to optimize costs and pump size):

- Use correctly sized and fitted vacuum piping. Avoid screw fittings.
- Avoid sharp bends and complicated pipe geometry
- Avoid velocity changes
- Use smooth bore or de-scaled pipes
- Avoid traps and kinks.

viii. Utilities

Utility supply, particularly pressure and cooling water temperature, affect pump sizing. For example, cooling water temperature greatly influences pump capacity, system pressure, exhaust emissions and safety.

The frequency of the available power supply can also be important in matching available capacity with that required by the process. Using a variable speed drive to control the rotational speeds of rotary pumps can provide excellent capacity and pressure control and minimize energy and capital costs.

6 CORRECT SELECTION OF VACUUM EQUIPMENT.

Selection is strongly influenced by the end-user’s requirements and constraints such as processing objectives, capital and operating costs, (cost of ownership), regulatory compliance and pressure-capacity ranges, (Table II and Fig. 2).

For example, a rotary vacuum filter may require a large capacity (>3,000 m³h⁻¹) at low vacuum (high pressure). A liquid ring vacuum pump is the optimum choice to meet capacity, pressure and cost of ownership criteria.

Staged systems can be used for high vacuum (low pressure) applications like evaporators or distillation columns needing large capacities. These may be all “wet” systems like steam ejectors and liquid ring pumps or all “dry” like mechanical boosters and dry backing pumps. They can also be combinations of wet and dry, e.g. boosters backed by liquid ring pumps, (see Fig. 2).

Wet vacuum raising equipment include steam, or water ejectors, liquid ring vacuum pumps, rotary vane and rotary piston oil-lubricated vacuum pumps.

Dry vacuum raising equipment include Roots blowers and vacuum (mechanical) boosters and dry

running vacuum backing pumps using either, Roots, claw or screw mechanisms.

There are a lot of similarities between wet and dry vacuum systems, such as multistage steam ejectors or multistage roots blowers, providing both large volumetric throughput and high compression ratios. The main difference between the two technology types is the use of fluids for either compressing (ejector and liquid ring pumps) or for lubricating as with rotary vane and rotary piston vacuum pumps. Both types of technologies have frequently been combined to boost vacuum or capacity, e.g., steam ejectors backed by dry vacuum pumps or Roots dry running mechanical boosters backed by liquid ring vacuum pumps.

The options for selection are numerous and whether operating alone or part of a multistage system both wet and dry offer different advantages, (see Table II). Being able to choose the correct vacuum system type or combination is a must, if the end-user wants maximum flexibility and reliability at the right cost of ownership.

Over the last 30 years environmental issues have led to restrictions and limitations on liquid and gaseous emissions. The cost of energy, water and effluent treatment have risen greatly along with the penalties for exceeding emissions limits. These two factors alone, affecting the cost of ownership, strongly influence the selection of wet or dry vacuum pumps. Fig. 3, for example, compares the cost of ownerships of a steam ejector system and a dry vacuum pump system for a biodiesel application requiring $2,100 \text{ m}^3\text{h}^{-1}$ at 20 mbar. The capital cost of the dry pump system is greater but its running cost is significantly less than a steam ejector's.

Safety is by no means the least important factor in the selection process but ATEX (EU countries) for example has led to considerable misunderstandings as to where responsibilities start and finish. Equipment manufacturers must liaise with users and plant manufacturers to ensure equipment is correctly selected to meet safety regulations. Complying with ATEX requires the end user to define hazardous zones, temperature classes and gas groups. The supplier must supply certified equipment to meet the user's ATEX categories in explosive atmospheres.

7 SYSTEM DESIGN AND OPERATION

The future of any plan will always be linked to cost justification. Therefore, even though the correct sizing and selection of the equipment is important, unless integration into the plant is correct, safety, flexibility, reliability and cost control become very difficult to ensure.

Correct system design is therefore the concluding step in ensuring, reliability, safety, and mechanical, electrical and regulatory standards, such as PED, ASME, DIN, ATEX and IPPC, and system integration are met. A complete design may include accessories such as sensors, filters, condensers, receivers, knockout pots, separators, flame arresters, silencers, skids, valves and control systems.

The mechanical design focuses on three basic functions which are integrity compliance to minimise air leakage, dimensional and material compliance to satisfy regulatory and safety standards and functionality to ensure the system is fit for purpose with minimized

pressure drops. The system design is based on meeting process objectives like pressure, processing times and also flexibility to cope with process upsets.

Apart from meeting the motor, instrumentation and control requirements, power supply should meet both peak and running demands. System control either from a remote DCS or local control panel is highly recommended to ensure correct functionality and safety.

The final requirement to comply with is limiting liquid and gas emissions by using exhaust management systems. These can be either part of the vacuum equipment systemisation or provided by others to agreed design criteria. Knowing the vacuum equipment discharge conditions, (pressure temperature and mass loads), the appropriate exhaust management system can be designed to meet environmental and process requirements. This may involve operating with high back pressures and chilled cooling media to maximise condensation using an exhaust condenser. In some cases, the exhaust gas can also be recycled and reheated to aid solvent recovery as done on filter dryers.

8 CONCLUSIONS

Vacuum equipment may only represent a small percentage of the total biomass conversion process but it is often a vital component.

Sizing of the vacuum equipment, including piping and accessories, is determined from process parameters such as air leakage, pressure, temperature and vapour flows. Correct sizing is vital to ensure optimum design, functionality and meeting processing objectives, (quality, yield, cost, etc.)

The correct vacuum levels and technology (wet or dry) affect energy consumption, processing times, quality, yield, environmental impact, safety and profitability.

The final system design is the culmination of idea transfers and co-operation between process designers, equipment suppliers and end-users so all objectives can be fully understood and complied with.

9 REFERENCES

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Application	Rotary Vane Pump	Rotary Piston Pump	Mechanical Booster	Liquid Ring Pump	Steam Ejector	Dry Pump	Pressure Blower	Centrifugal Blower	Process Blower	Screw Compressor
Biogas Recovery			✓	✓			✓	✓		
Central Vacuum (flammables)			✓	✓		✓				
Central Vacuum (non-flammables)	✓	✓	✓	✓		✓		✓		
Combustion Processes							✓	✓		
Corrosives Gases			✓	✓	✓	✓			✓	
Crystallization		✓	✓	✓	✓	✓				
Degassing	✓	✓	✓	✓	✓	✓				
Dewatering & Filtration			✓	✓			✓	✓		
Distillation	✓		✓	✓	✓	✓				
Dehydration, (ethanol)			✓	✓	✓	✓				
Deodorization			✓	✓	✓	✓				
Drying, including esters			✓	✓	✓	✓				
Dust Extraction							✓	✓		
Evaporation		✓	✓	✓	✓	✓				
Flammable Gases			✓	✓	✓	✓			✓	
Flue Gas Desulphurisation				✓	✓			✓		
Gas Recovery/Recirculation			✓	✓		✓	✓		✓	
Glycerin purification			✓	✓	✓	✓				
Materials Handling	✓			✓			✓		✓	
Mechanical Steam Recompression							✓		✓	
Pervaporation			✓	✓	✓	✓				
Pneumatic Conveying				✓			✓		✓	✓
Power Generation, (CHP plants)				✓	✓		✓		✓	✓
Pressure Swing Absorption			✓	✓	✓	✓				
Reactor Service			✓	✓	✓	✓				
Solvent Recovery			✓	✓	✓	✓				
Vacuum Filling	✓	✓	✓	✓		✓				
Waste Water & Wet Cake Treatment				✓			✓	✓		✓

✓ ✓ Widespread Applications
 ✓ Some Applications

Table 1. Vacuum and pressure applications and technologies in biomass processing.

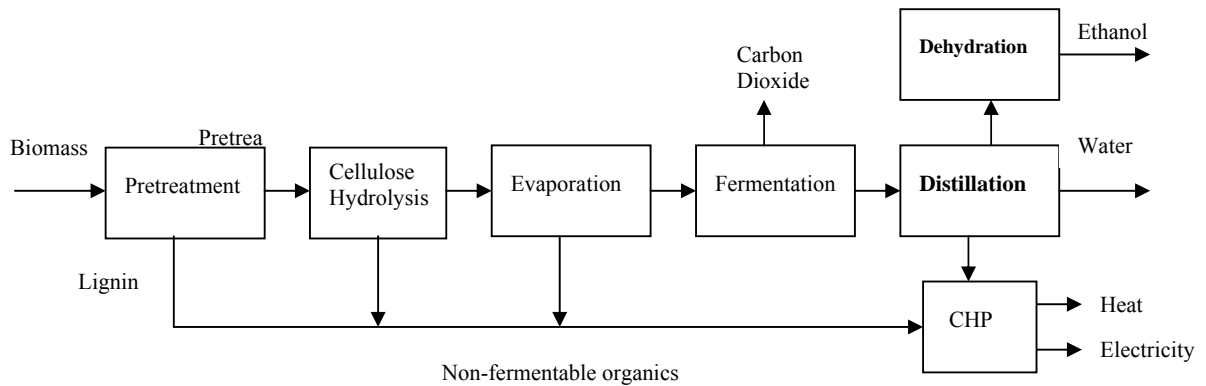
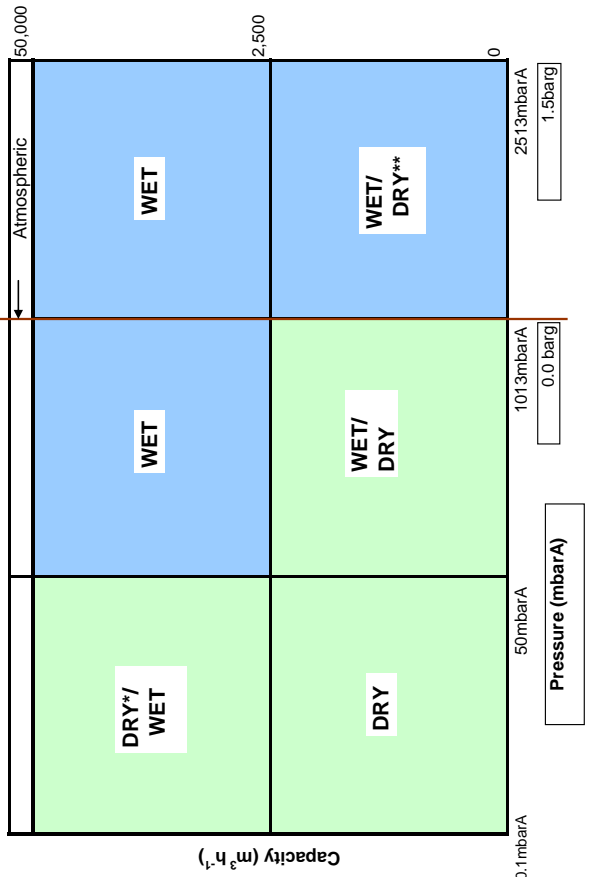


Figure 1. Biomass to ethanol and combined heat and power (CHP) process scheme.

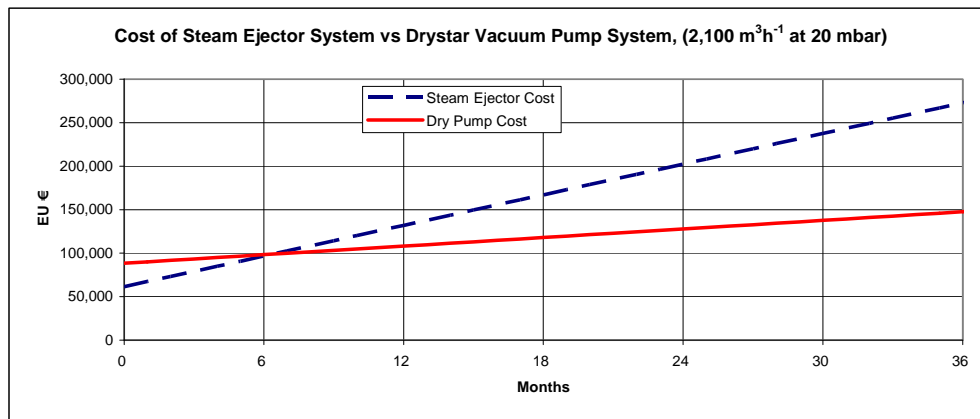
Table 2. Vacuum equipment technologies - size range, types and benefits

Most likely optimum selection type		Benefits	
		WET	DRY
Capacity (m ³ h ⁻¹)	50,000	Liquid Ring Pumps LRP's <ul style="list-style-type: none"> * Large capacity range * Very tolerant to process upsets, (liquid and solid carryover) * Oil free gas compression * Wide range of materials of construction * Service liquids are variable to cover solvent recovery or reduce effluent 	Dry vacuum pumps <ul style="list-style-type: none"> * High operational vacuum capability - not limited by cooling water temperature * Process gases are maintained in the vapour phase to allow optimum exhaust vapour recovery and eliminates corrosion * No effluent generation * Safe pumping of flammable mixtures or corrosives without the need for sophisticated materials * High thermal and mechanical efficiency * Lowest cost of ownership
	2,500	Ejectors <ul style="list-style-type: none"> * Multistage combinations offer large capacity and high vacuum capabilities * Reliable and simple to operate and maintain * Motive fluid can vary from steam to atmospheric air or even liquids * Available in a wide variety of materials 	Roots vacuum boosters <ul style="list-style-type: none"> * High volumetric capacities and vacuum capability * Multistage combinations with wet or dry backing pumps * Sophisticated materials of construction are not required because of the operating pressure and temperature * Reliable and well proven even on the most arduous duties found in the process industry
0.1mbarA	0		



* ** Dry vacuum pumps operating above atmospheric pressure are limited to ~2 barg maximum discharge pressure with speed control

* Multistage combinations
 Dry + Dry
 Wet + Wet
 Dry + Wet
 Wet + Dry



Paid back after **6.4** months

With savings thereafter of **50,742** EU €/year

Figure 3. Typical cost of ownerships for a steam ejector vacuum system and a dry vacuum pump system requiring 2,100 m³h⁻¹ at 20 mbar on a biodiesel application.