Abstract

Achieving high performance process control (HPPC) requires that the control system operate the plant at optimal efficiency over the full range of steady state and dynamic conditions. Air separation processes present particular challenges because of their energy intensive nature and demanding production schedules. The HPPC challenges for both cryogenic and adsorption processes are presented, recent applicable research is summarized, and directions for future research are proposed. The value of the operability index to improved HPPC is also presented and discussed.

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Air separation has become a process integral to many manufacturing processes. The largest markets for oxygen are in primary metals production, chemicals and gasification, clay, glass and concrete products, petroleum refineries, and welding (Air Products, 2005b). The use of medical oxygen is an increasing market. Gaseous nitrogen is used in the chemical and petroleum industries and it is also used extensively by the electronics and metals industries for its inert properties. Liquid nitrogen is used in applications ranging from cryogenic grinding of plastics to food freezing. Argon, the third major component of air, finds uses as an inert material primarily in welding, steelmaking, heat treating, and in the manufacturing processes for electronics.

The separation of air into its components is an energy intensive process. The companies designing air separation processes have aggressively reduced the required energy to the point that it is possible to sell a truckload of liquid nitrogen for is less than many common consumer products. This surprising result has been accomplished by advances in process design, process operation, manufacturing approaches and techniques, and improvements in supply chain management. Process designs have increasingly utilized mass and energy integration, substituted more efficient unit operations for less efficient ones, furthered the development of machinery and equipment used in the process, spawned alternatives to cryogenic production for gaseous products, and required the implementation of advanced control strategies. Process operations have increased the ability to operate efficiently at a wider range of production requirements, significantly improved productivity through pervasive automation and advanced control, developed the capability to efficiently handle rapid production rate and product split changes, and leveraged advances in remote communications. Supply chain improvements have ranged from improved purchasing practices to optimized scheduling of product delivery to coordinated operation of separate facilities.

Much has been written concerning the design of air separation processes and certainly the worldwide patent activity for flowsheet and equipment innovation continues.

Advanced control has been practiced in the air separation business for decades. The first application of computer control for an air separation plant was completed in the early 1970s. Since that time, most advanced control technologies have been applied in an attempt to improve the efficiency and productivity of air separation facilities.

1. High performance process control challenges

1.1. Process characteristics

There are two primary methods of separating air into its two main components. If a lower volume, gaseous oxygen or nitrogen product is required, then an adsorption process driven by the pressure difference between the adsorption step and the desorption/reactivation steps may be used. On the other hand, for
liquid products, larger volume gaseous products, high purity products, or the recovery of argon, cryogenic processes will be used. Fig. 1 (Air Products, 1997) indicates the ranges of capacity and purity for which the different methods of oxygen production are most suited. A similar graph describing the ranges for which the different nitrogen processes are applicable can be seen in Fig. 2 (Air Products, 2002a). Methods such as membrane separation are also available but they are currently used far less pervasively than the other two approaches. Therefore, subsequent comments in this paper will only address the control challenges presented in the adsorption and cryogenic processes. These control challenges presented are the result of demands to obtain maximum performance from an existing plant, thus requiring the advanced control system to achieve high performance process control. HPPC seeks to produce the optimal mix of products at limiting specifications while consuming the minimum energy at steady state conditions and at every dynamic operating point. The HPPC challenges for these two processes are similar in many ways yet distinctly different in other ways, requiring different advanced control approaches.

1.1.1. Cryogenic processes

The cryogenic process is comprised of unit operations that compress, purify, and separate the air feed into the required gaseous and liquid oxygen, nitrogen, and argon product flows. The air feed is compressed prior to the removal of the primary impurities of $\text{H}_2\text{O}$ and $\text{CO}_2$ via adsorption. The air is then cooled by heat exchange with exiting product and waste streams and then sent to a set of mass and energy integrated distillation columns where the air is separated into oxygen, nitrogen, and argon. Liquid products are sent to storage and the gaseous products are re-warmed by the feed streams and then compressed to the required final product pressure(s). A typical flowsheet for high purity oxygen, nitrogen, and argon production is shown in Fig. 3. The exact compressor, expander, and column configurations are determined by the product purities, flows, and pressures required. All configurations have common characteristics that impact the performance of process control systems.

A distinguishing feature of an air separation process as shown in Fig. 3 is that many of the purities have a response time measured in hours. When a response time of this duration exists, keeping track of the full impact of adjustments become very difficult for an operator and virtually impossible when spanning shifts. It is often possible, for example, to increase the flow to the argon column and improve argon recovery in the short term. If the increase is too great, inevitably the nitrogen composition in that stream will increase as the nitrogen profile is lowered in the LP column. This increased nitrogen will then cause major operating problems since there is not enough driving force in the temperature differential of the argon column overhead condenser to liquefy the additional nitrogen. The impact from increased flow to the argon column exhibits the long time to steady state as a result of the significant liquid holdups that exist on the column packing (or trays) and the reboiler/condenser sump inventory the column system coupled with the recycle of the liquid stream from the bottom of the argon column to the low pressure column. This is a textbook case of the negative impact of a recycle stream and decoupling the two columns can significantly reduce the time to steady state. Another major impact on the operation is a change in air flow into the plant. The air flow change may
Fig. 3. Simplified process for the cryogenic production of oxygen and argon.

have been purposely initiated or it may be the result of ambient temperature swings during a time when the air controller is constrained, but the change impacts the entire column system as the material and energy balances readjust the flow and purities.

The cryogenic nature of the process drives the tight energy and mass integration of the three-column system. The condensing stream at the top of the high pressure column is used to provide reboil to the bottom of the low pressure column. That same condensing stream provides reflux to the top of the low pressure column, while the high pressure, crude liquid oxygen stream provides condensing duty for the argon column before passing to the low pressure column. The argon column gets its feed as an intermediate vapor stream from the low pressure column which is mostly returned to the low pressure column as liquid condensed by that crude oxygen stream. Clearly there is significant interaction (Fig. 4) when almost any of the manipulated variables are adjusted or a disturbance affects one of the column controlled variables.

Typical product composition specifications are for the nitrogen product to contain less than 10 ppm oxygen, the oxygen product to be better than 99.5% oxygen, and the argon to contain fewer than 10 ppm impurities. High purities specifications such as these are known to produce nonlinear responses between the composition and column feeds. In addition, the presence of nitrogen in the feed to the argon column produces extreme nonlinear behavior in the argon column when it exceeds a certain level, the separation efficiency of each separation stage in the distillation columns is nonlinear over the wide operating ranges required, and the valves and compressor guide vanes exhibit nonlinear characteristics over the full range of operation. While it is true that these nonlinearities are not evident immediately around the design point, it is also true that once a plant is in operation, production will be pushed to limiting constraints in order to maximize the profitability of the plant and the control strategy will have to account for these nonlinearities. An all too common mistake made during control implementation is to fail to account for nonlinearities that occur away from the design operating conditions.

An air separation plant supplying gaseous products is either connected to a large pipeline system supplying multiple customers or it may be directly supplying product to a single customer. Two examples of the different types of product supply are shown in Figs. 5 and 6 (Air Products, 2005a). Regardless, the product must be supplied to the customer when it is needed, so the plant has to respond rapidly to the changing product demand. Given the long time to steady state, it is possible that the plant may rarely ever settle into a steady state condition. This requires that the control strategy handle both the dynamic and steady state effects in order to achieve efficient operation. At the same time, the energy intensive nature of cryogenic liquid production often requires changing production rates to take advantage of variable power pricing or supply chain demands. Take the case of several production facilities feeding a gaseous product pipeline with multiple customers. In general, the most efficient/lowest cost plant will be baseloaded at a fixed production rate and the remaining facilities will be the first to change production rates. If these higher cost facilities also have smaller capacities, then it is likely that these facilities will be required to change between minimum and maximum production rates often and as quickly as possible. Alternately, when plants feed a common pipeline have different power cost structures, it may be necessary to ramp production from these facilities as quickly as possible to minimize costs.

Another interesting aspect of the cryogenic air separation process is that many of the compositions in the distillation column exhibit colinear behavior, that is a manipulated variable
affects all of the compositions in a similar fashion. They cannot be controlled independent of each other which requires an understanding of the process design in order to produce a reliable control installation.

Although air separation is a clean process which does not foul measurement devices as many petrochemical processes do, the cryogenic nature and energy intensity of air separation produce some significant measurement challenges. The primary impact of this drive for efficiency results in limited pressure drop availability for flow measurement since each flow meter increases the pressure and ultimately the power required to produce the products. Cooling of the cryogenic liquid streams is provided by returning low pressure vapor streams, so the capability to sub-cool those liquid streams is limited. As a consequence, the use of flowmeters to measure the liquid flows can produce unreliable or inaccurate readings. Also, the analyses of limiting impurities are difficult to do in a cost effective manner. An excellent example of this is the measure of nitrogen in the oxygen, nitrogen, argon mixture feeding the argon column. The difficulty in cost effectively measuring the nitrogen can be seen in the number of patents (Al-Chalabi, 1988; Howard et al., 1994; Seiver & Swafford, 2005) that have been issued to measure or estimate the nitrogen composition in the feed to the argon column.

Compressor and expander design, configuration, and selection are important factors in the ultimate efficiency, flexibility, and reliability of a new process design. Trade-offs in design of
a single-shaft compressor performing multiple services versus multiple machines, each performing one service, is one of the typical issues that impact on the eventual plant operability. In a similar way, high peak efficiency may be tweaked with design changes such as special seal designs that can limit the ability to easily change the compressor or expander flow rates. It is entirely possible to produce a process flowsheet built around a custom designed compressor scheme that delivers an excellent “paper” efficiency but severely limits the ability of the plant to operate at more than a single point. A side impact of a design like this is that it can be extremely difficult to start-up.

Major disturbances to the process are ambient temperature and pressure and temperature fluctuations caused by sequencing of the front end clean-up system. A cryogenic process still has to reject heat at ambient temperatures in the same way as higher temperature processes, but the impact of changes in ambient temperatures on cryogenic process performance can produce significant disturbances. Removal of CO$_2$ and H$_2$O from the air feed prior to cool down is typically done by passing the air through molecular sieve adsorption bed. Once the bed is saturated with H$_2$O and CO$_2$, it must be taken off-line in order to remove the impurities. Placing the bed back in service typically introduces both a pressure and temperature disturbance in the plant that must be accommodated.

These challenges are summarized in Table 1. The efficiency and cost effectiveness of air separation designs have continued to improve driven by intense competition among design and operating companies. The recent spike in energy costs will no doubt catalyze further improvements. This improvement can be seen by examining the patent literature and noting the type of patent and the complexity of design. Patents for processes that produce the same products can be seen to exhibit increasing complexity. Even though the complexity is increasing, the performance demands are not being relaxed, in fact they are becoming more stringent and the control system must deal with this complexity.

### Table 1

<table>
<thead>
<tr>
<th>Cryogenic ASU characteristics</th>
<th>Driver of characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long time to steady state</td>
<td>Liquid holdup in column and recycle loops between columns</td>
</tr>
<tr>
<td>Multivariable interaction</td>
<td>Heat and mass integration</td>
</tr>
<tr>
<td>Nonlinearity</td>
<td>High purity products, non-condensible intermediary, separation stage efficiencies, valve characteristics</td>
</tr>
<tr>
<td>Dynamic operation</td>
<td>Supply of products as required by customers, time-of-day power pricing</td>
</tr>
<tr>
<td>Co-linearity</td>
<td>Compositions and temperatures in the LP column</td>
</tr>
<tr>
<td>Measurement challenges</td>
<td>Limited pressure drop availability for flow measurement whether gaseous or saturated liquid flows, analyses of limiting impurities</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Efficiency versus flexibility (guide vanes/seals, single shaft vs. separate, full integration with cycle)</td>
</tr>
<tr>
<td>Diurnal variations</td>
<td>Ambient temperature disturbances</td>
</tr>
</tbody>
</table>

### 1.1.2. Pressure driven adsorption processes

Oxygen or nitrogen production by an adsorption process is driven by the ability of process specific molecular sieve to preferentially adsorb the non-desired molecules at a feed pressure that is higher than the subsequent pressure during the desorption step. The pressure differential may be the result of compressing the air feed to high pressure when nitrogen is the desired product in a process known as pressure swing adsorption (PSA). A typical PSA process is shown in Fig. 7 (Air Products, 2002a). When oxygen is the desired product, the air feed is not significantly compressed but the desorption pressure is reduced to vacuum in a process known as vacuum swing adsorption (VSA) as shown in Fig. 8 (Air Products, 2002b). Both the PSA and VSA processes are cyclical in nature, undergoing a sequence of steps such as adsorption, purge, equalization, evacuation, and re-pressurization. Eventually, these processes will reach a cyclical steady state or CSS where the composition profiles within the vessels are constant at a given stage in the adsorption step. Some of the control challenges in adsorption processes are sim-
ilar to those in cryogenic processes although they are often due to entirely different physical reasons.

Each bed in a PSA/VSA accepts air feed for a short period of time, on the order of 10 s. This might lead one to conclude that the response times are short. The key issue here is that it takes many cycles for the composition and temperature profiles to reach CSS, on the order of hours. This difference in time scale is graphically depicted in Fig. 9 which contains a plot taken from Webley (Beh & Webley, 2003b). The control strategy must account for these disparate differences in time scale. A change in one of the step times in the bed sequence impacts all other beds, resulting in significant interaction from the manipulated variables. Varying demands for product flow require the unit to rapidly vary between maximum and minimum production while maintaining purity. Similar to the cryogenic processes, measurement of key limiting variables, in this case the location of the composition front, is a challenge to perform in a cost effective manner.

The short on-stream times for each bed means that the speed of response and repeatability of the control valves is an important issue. Variations in the speed of opening of even one of the valves can cause significant disturbances to the process.

1.2. HPPC approaches

In order to meet the increasing demands described in the previous section, the control systems for cryogenic air separation processes have gone through the transformation from simple pneumatic single loop controllers to the current powerful digital control systems. One of the most significant improvements in high performance process control of an air separation plant was the implementation of direct digital control schemes. These DDC schemes utilized an approach in which the computer calculated control moves and sent them directly to the valves via digital-to-analog converters. This approach was highly successful (Chatterjee et al., 1985; Vinson & Chatterjee, 1986) and enabled superior operation of key loops that had never performed reliably in closed loop. DDC was widely practiced until base control systems progressed from analog-to-digital, which enabled improved control loop performance because of
increased tuning capabilities. The utilization of the more capable digital controllers ultimately led to supervisory computer control strategies in which the advanced control logic in the computer sent setpoint changes to the digital controllers rather than controller outputs. Throughout this time, practitioners were pushing the boundaries of HPPC by implementing programs intended to automate plant start-up (Russek et al., 1985), efficiently operate unattended facilities (Vinson & Chatterjee, 1984), increase the ramping of plant production rates and product split changes, minimize the power required for a specified production, and maximize the production of the more valuable products. These programs were primarily SISO-based with requisite overrides, interlocks, feedforwards, and rules. In fact, there were even efforts to translate these programs into expert system based logic (Cartledge & Vinson, 1991). These systems were successful and many still operate today but the increased power of computers ultimately permitted MIMO-based model predictive control programs to be implemented in a cost effective manner and the next level of HPPC was delivered. Model Predictive Control, or MPC, can achieve both dynamic and steady-state optimization within specified constraints. In addition, the configuration-based rather than program-based nature of this software significantly reduced the support effort, delivering the best of both worlds—improved performance and reduced support.

This history of improving control system performance can be described as the utilization of improving computing power to more accurately predict future behavior of the process from improving models (Table 2). When pneumatic controls were utilized for the base control system, critical loops were often run in manual mode because of the limited tuning capabilities available. Models migrated from SISO thinking in the mind of a human operator to multivariable accounting via matrix math in a supervisory computer.

As these models became more sophisticated and mathematically explicit, additional plant testing time was required. One of the most significant costs in the implementation of MPC is the

![Graph](image1.png)

**Fig. 9. Varying process response time scales in a VSA process.**

<table>
<thead>
<tr>
<th>Base control system</th>
<th>Mode of control</th>
<th>Model complexity</th>
<th>Model residence</th>
<th>HPPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pneumatic SISO</td>
<td>Manual</td>
<td>Short term dynamics, limited interaction</td>
<td>Human operator</td>
<td>Low</td>
</tr>
<tr>
<td>Electronic SISO</td>
<td>SISO with DDC</td>
<td>Limited interaction, feed forward, short term dynamics</td>
<td>FORTRAN/basic routines</td>
<td>Medium</td>
</tr>
<tr>
<td>Electronic SISO</td>
<td>Expert system</td>
<td>Limited mathematics, human reasoning approach</td>
<td>Expert system</td>
<td>Medium</td>
</tr>
<tr>
<td>DCS</td>
<td>Linear MPC</td>
<td>Dynamic models describing future behavior and relationship between variables</td>
<td>Dynamic mathematical matrix</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 2
Model accuracy and HPPC
cost to develop these models from field testing of the operating facility. Much work has been done to reduce the time and cost of producing the data for these models. One approach to reduce testing time to conduct a multivariable test (Kothare & Mandler, 2004).

The current state-of-the-art for HPPC systems in cryogenic air separation plants is model predictive control, while the smaller PSA/VSA plants utilize a combination of single loop and sequence-based control. Every major supplier of large air separation facilities in addition to Air Products and Chemicals Inc. has implemented MPC (BOC, 2003; Goodhart et al., 1999; Seiver & Dupre, 2000). The scope, objectives, and complexity of the MPC applications varies between companies and installations, but this clearly is the preferred approach. Pursuing efforts to further increase the benefits from MPC, companies are incorporating loops into MPC that perform well on their own but deliver even more performance when incorporated into the MIMO architecture (Seiver & Marin, 2001), extending control to multi-plant facilities and product distribution pipelines (Zhu et al., 2001a), extending control to smaller facilities, and including MPC in facilities that have only a single product. In an effort to wring even more profit from the operation, some application of nonlinear MPC has recently occurred (Bian, Henson, et al., 2001a).

2. Current research with application to air separation

2.1. Operability index

The benefits and challenges of evaluating the impact of design complexity on the operability of a facility were the subject of work by the author (Vinson, 1997, 2000). One of the results of that work was the definition of a measure called the operability index (OI). In order to calculate the OI, a number of operating spaces were defined, some of those spaces are identified here:

(1) Available input space (AIS)—represents the range over which the inputs of the process are able to change.
(2) Achievable output space (AOS)—the output space that can be reached using the entire AIS.
(3) Desired output space (DOS)—the desired operating window for the process outputs.
(4) Desired input space (DIS)—the set of input values required to reach the entire DOS.
(5) Expected disturbance space (EDS)—the anticipated ranges of disturbances.

A working definition of the operability index is given by the following equation:

\[
OI = \frac{\mu(AIS \cap DIS)}{\mu(DIS)} \quad \text{or} \quad \frac{\mu(AOS \cap DOS)}{\mu(DOS)} \quad (1)
\]

Here \( \mu \) is a measure function calculating the size of the corresponding space. For instance in two dimensions, it represents the area, and in three dimensions, it represents the volume. More details concerning the individual spaces, calculation of the OI for different processes under different conditions, and extension to dynamic analysis can be found in a number of references (Georgakis et al., 2003, 2004; Vinson, 2003; Vinson & Canney, 2004). Since MPC is employed so pervasively in HPPC systems for air separation facilities, the ability of the operability index to assist in the design and operation of MPC was explored. The bulk of existing installations and current applications of MPC utilize linear dynamic models of the relationships between process inputs (classified as manipulated variables, MV’s, and disturbance variables, DV’s) and outputs (called controlled variables, CV’s). These models are generally developed from plant data and take the form of step coefficient response models, discrete transfer functions, or state space models. The future dynamic response of each CV is predicted for a given time horizon and the error between each CV and its target (fixed constraint, fixed trajectory, funnel constraint, etc.) is minimized over a discretized future time horizon. The relative importance of reaching and maintaining the CV targets and the relative freedom of movement for each MV are determined by weighting factors.

The steady state targets for the MV’s are determined based on economics either within the MPC algorithm or from an external cost optimization or are predefined as ideal steady state values. These targets will fall within defined upper and lower constraint limitations. The CV steady state targets will also not have specific setpoints, but will have calculated values that lie within defined upper and lower constraint limits. These characteristics of MPC mesh with those of the steady state operability framework proposed by Vinson and Georgakis (2000) to enable the analysis of operability related MPC problems via application of the OI. In a typical installation of MPC within an air separation facility, there will be more controlled variables defined than manipulated variables. The OI has also been shown to apply (Vinson & Georgakis, 2000) in this case.

Certain characteristics of linear MPC controllers make the concepts of OI particularly applicable within this framework. Linear process models make the calculation of the AOS from AIS and the DIS from DOS relatively rapid and straightforward, fixed upper and lower constraints on MV’s and CV’s permit calculation of polytopes for the input and output spaces, and finally, the determination of the active set of MV and CV steady state targets at each controller iteration permits the steady state characteristic of the OI to provide useful information in a dynamic control situation.

In addition to the potential enhancement of the operation of linear MPC through application of the OI, operability of a process that will utilize linear MPC as the advanced control algorithm could be improved if the OI was evaluated during the synthesis stage. Insights gained through this analysis could also lead to improved controller design. It should be noted that nonlinear MPC algorithms typically linearize the models around the current operating point, making it possible to extend the use of OI to many nonlinear MPC algorithms.

Development of the OI has been primarily oriented toward application at the process synthesis stage. Quantified evaluation of process operability will speed the implementation of improved processes because of increased confidence in the ability of the process to produce products at the correct specifications over a range of operation. Although inherent operability does not
depend on control scheme selected but on the process gains and
constraints, MPC implements control of the process constraints
in standard multivariable, model-based algorithm rather than
a more individualized override, feedforward, gain decoupling
approach. The OI can be applied in either square or non-square,
nonlinear or linear processes; but it is most straightforward to
apply with a linear model—exactly like the current, widely
applied MPC algorithm. One way to apply the OI would be to
specify those outputs that are critical to control tightly because
of economic or safety impact, those CV’s that can be controlled
less tightly but must still be within constraint limits, and the CV’s
that really do not impact economics or safety but are important
for operation. Then the calculation of the OI could be incorpo-
rated into an economic optimization for combined process and
controller design.

It is important to determine realistic limits for process con-
straints so that the controller will be able to achieve the desired
objectives. Economic performance of the process increases
when the range of limiting constraints can be expanded. The
OI should give insights into the ability of a MPC controller to
control at constraints (which may further cause the engineer to
make design improvements). A second application of the OI for
MPC controller design is to evaluate the best configuration or
transformation of MV and CV’s that give the broadest possible
operation utilizing a specific MPC model by better linearizing
the steady state process gains. This has particular application to
air separation control because of the nonlinear nature of mass
and energy integration of the high purity distillation columns.
It should be noted that the fact that a correctly linearized model
can better represent a nonlinear process model over wider range
of operation is not contradictory with the fact that the OI is
independent of control structure.

The introduction of unmeasured disturbances, equipment and
machinery degradation, and process nonlinearities can cause an
MPC controller to perform worse than initially designed. An
industrial MPC controller generally has the ability to calculate
and track prediction error, thus providing an indication of the
cause of performance deterioration. Further research is needed
into quantifying the enhanced real time controller performance
assessment available through identifying the region of the
DOS that the controller can no longer reach at each controller
execution.

2.2. Other research

Research that has application for improving HPPC for air sep-
aration is currently in progress by a number of researchers. This
research can be divided into two categories: (1) research which
utilizes air separation processes as an application on which to test
algorithms and models, or (2) research which does not specific-
ically make application to air separation but could definitely be
applied for this process. Selected research is briefly presented
and discussed in the following section.

2.2.1. Specific application to air separation

The multivariable nature of cryogenic air separation has
been investigated by a number of researchers. Roffel et al.
(2000) developed a first principles dynamic model of a two
column cryogenic air separation process. A number of SISO
control schemes were investigated along with a MIMO pre-
dictive control approach. The model predictive approach was
found to have improved performance by taking advantage of
the variable interactions and improved ability to avoid the sat-
uration of control valves. Different approaches were used in
modeling high purity cryogenic distillation columns by another
research group (Bian, Henson, et al., 2005; Bian, Khowinija,
et al., 2005; Zhu et al., 2001b). The nonlinearity of the distil-
llication process was addressed by two different approaches:
first, a reduced order wave-based nonlinear model was devel-
oped, and second, reduced order compartmental-based models
were developed using singular perturbation theory. The wave-
based, nonlinear model was used to evaluate the performance
of nonlinear MPC. This was done by designing a NMPC for
a simulated nitrogen purification process (no low pressure or
argon columns). Results were compared to a classical cascade
PID controller but not to linear MPC. Trierweiler (Trierweiler
& Engell, 2000) demonstrated a new controllability index, the
robust performance number (RPN), on a linear model derived
from step tests of a nonlinear model and also applied RPN to
assist the tuning of MPC for the process (Trierweiler & Farina,
2003). The flexibility of cryogenic air separation was researched
(Sirdeshpande et al., 2005) by applying flexibility analysis to a
two column process. The flexibility analysis was extended with
an approach that incorporates convex hull analysis, just as con-
vex hulls were used to calculate the operability index (Vinson
& Georgakis, 2000).

Control of adsorption air separation has increasingly been
the subject of research with much of the focus on improving the
modeling in order to reduce the time it takes to converge to a
calculated cyclical steady state (Beh & Webley, 2003a; Jiang et
al., 2003; Wilson & Webley, 2002). Very little has been published
concerning improved control of PSA or VSA units.

2.2.2. Parallel application to air separation

There is much that is applicable to air separation in advanced
control research. Advances in operability analysis, integrated
design and control, nonlinear control, multivariable controller
performance monitoring, identification of the optimal location
of sensors, lower cost sensors, and improved state estimation
could all be useful in the design and operation of air separation
facilities. However, mention will be made of three recent efforts
that have the potential for immediate impact.

The recent increase in energy costs will accelerate the devel-
oment of more efficient air separation processes. Operability
analysis that extends the work previously discussed (Vinson
& Georgakis, 2000) has been ongoing (Georgakis et al., 2004;
Sirdeshpande et al., 2005; Uztürk & Georgakis, 2002) and
can assist in the analysis of the operability impact of more
energy efficient future designs. Research in advanced control
that reduces the cost to implement MPC enables additional pro-
cesses and plant sizes to receive the HPPC benefits of MPC. This
is the focus of research such as the application of parametric pro-
gramming for offline explicit derivation of the MPC controller,
yielding an online controller that does not require on-line solv-
ing of the optimization problem (Sakizlis et al., 2003, 2004). An alternate approach to the same problem is given to reformulate the MPC problem with linear matrix inequalities to yield an asymptotically stable invariant ellipsoid (Wan & Kothare, 2003). Finally, there has been research activity in the application of MPC to optimize supply chains (Perea-López et al., 2003; Wang et al., 2005). Air separation business incorporates significant supply chain utilization either via gaseous pipeline supply to customers or liquid tanker delivery.

3. Proposed directions for future research

Air separation is often viewed as a mature technology, yet significant advances continue to be made in the design efficiency and operating optimization of these processes. The recent rise in energy prices will drive further improvements in the industry which may catalyze additional research aimed at further improvements in control and operability of air separation processes. Suggested directions for future research in HPPC are described below.

The air separation industry is characterized by the design and startup of a significant number of new plants each year. In addition, in order to optimize product supply into a pipeline system, it is not uncommon for the operating companies to frequently start and stop one or more plants feeding into the pipeline. The current practice in industry is to install HPPC after a new facility has completed start-up, passed the performance test, and has achieved daily operation at the expected production rates and product splits. Although this yields highly profitable advanced control projects, significant benefits can be lost during the time it takes to arrive at the conditions favorable for advanced control implementation. The best practice in industry for HPPC today is the installation of MPC. Research into methods to startup a plant with fully functional MPC would ultimately lead to additional benefits to industry from faster commissioning times, reduced labor, and reduced energy consumption. The areas for research could include approaches for dealing with the significant model nonlinearities, differences between plant design and performance, and changing objective functions and/or performance requirements as the plant transitions through the startup phases. Operability analysis during the design stage and in operation has the potential to contribute toward the goal of achieving higher availability from HPPC than from the plant.

It is not uncommon for small and large air separation facilities to run in an unattended mode for significant periods of time. Even during the times when an operator is not present, the energy intensity of the air separation process requires that the products are still produced efficiently in the face of all disturbances and production rate requirements. High availability and performance of an installed HPPC system is essential to achieving this goal. Further research into the identification, classification, and correction of advanced control off-stream reasons would be well received by the industry. Fault-tolerant MPC that permits the identification and prediction of changing unit operating constraints could also be useful.

Most of the past research into linear and nonlinear MPC has focused on the traditional continuous processes. As sequence-based processes such as PSA continue to proliferate and extend into larger capacities, the need to optimize the efficiency of these processes will become even more important. Research that develops HPPC techniques for a sequencing environment could be useful. The sequence steps rather than time represent the independent variable in this process. Also, techniques that permit MPC to be applied to smaller and faster processes could yield significant benefit for the air separation industry.

There are still many variables not measured during operation because of the cost of sensors and/or the cost of installation. Lower cost analytical devices; non-intrusive, accurate flow measurement devices; and improved estimating methods to replace more costly hardware are just three possible research focal areas.

4. Summary and conclusion

The air separation industry has demonstrated continued improvement in process efficiency and operating cost. A large contributor to the improvements has been the utilization of advanced control techniques. Recent increases in the cost of energy will continue to fuel the drive for optimized design and operation. The ability to achieve maximum improvements is dependent upon continued progress in the research of advanced process control techniques.

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References
