ESSAYS

Sustainable process systems engineering develops advanced techniques for energy and water optimisation

by Prof Thokozani Majozi

Sustainable process systems engineering (SUSPSE) is one of the research focus areas in the University's Department of Chemical Engineering. This research group focuses on the development of advanced techniques for energy and water optimisation in complex chemical facilities using sustainable process systems engineering. The key dimension of SUSPSE that is embraced in the endeavours of this research group pertains to process integration.

Process integration was established in the late 1970s in response to the energy crisis. At that time, the sole focus was on minimising energy by maximising the process of heat transfer, thereby minimising external utility requirements. By drawing analogies between mass and heat transfer, this concept was expanded in the late 1980s to embed issues of waste management and the reduction of emissions. Recent advances in this field, which evolved as an independent discipline in the early 1990s, involve systems characterised by simultaneous heat and mass transfer, as are commonly encountered in clean coal technologies, such as the integrated gasification combined cycle.

The unique strength of process integration lies in its ability to recognise the unity of the overall process. In practice, unit operations function in unison and not as stand-alone entities. However, most of the developments in published literature tend to address continuous processes at a steady state. The research that is currently underway in the SUSPSE group entails multipurpose batch chemical processes, which are characterised by inherent time-dependent behaviour.

The research group is already conducting advanced research in these areas and has completed a number of projects.

A graphic target and design technique for complex cooling water systems

South Africa is one of the driest countries in the world. Rivers and dams are the main sources of water. The continuous pollution of the country's natural sources, as well as the growing demand for water, has led to stringent environmental regulations to limit consumption and set the acceptable contamination levels before water is discharged into the main water cycle.

Various techniques have been used to address the use and contamination of water in industry. In recent years, pinch analysis has been extended to the design of cooling water systems following its success in heat exchanger networks (HENs) and mass exchanger networks (MENs). One study investigated the consumption of water and effluent reduction opportunities in a nitric acid production plant. This led to the development of a cooling water network design technique for systems with multiple cooling water sources. A cooling tower model was also used to investigate the impact of the new cooling tower design on its performance. The results of this analysis show that the blowdown rate can potentially be reduced by 47%. The cooling water used in the cooling water network could also be reduced by 23% and freshwater makeup by 10%. Moreover, the cooling tower performance was increased.

An automated approach to the development of a unified mass and heat integration framework for sustainable design

The successful industrial applications of pinch analysis techniques in energy optimisation and waste-water minimisation have resulted in recent studies on combined heat and mass integration. Researchers have demonstrated that the operation of cooling water networks in series, rather than the conventional parallel operation of these networks, improves the performance of the cooling tower and the cooling water network in new and retrofit designs. This methodology is extended by utilising a mathematical method to determine the superstructure of the cooling water network supplied by multiple cooling towers, which often occurs in practice. It was further demonstrated that the optimum cooling water supply to a network of heat exchangers supplied by multiple sources is determined by considering the entire system of

→ *The sustainable process systems engineering (SUSPSE) research group (standing from left): Esmael Reshid, Jane Stamp, Knowledge Molokoane, Donald Nonyane and Prof Thokozani Majozi, and (seated from left): Vhutshilo Madzivhandila, Vincent Gololo and Bola Adekola.*

sources (cooling towers) and coolers (heat exchangers). This optimum is less than the sum of the individual minimum cooling water supplies for each subset of coolers and their respective sources. The structure of the model allows the formulation to be cast as a mixed integer linear programming (MILP) problem, for which global optimality is guaranteed.

Developing a new class of batch plants via the exploitation of latent storage capacity

Batch chemical processes are commonly encountered in the production of fine chemicals of a high commercial value, for example, pharmaceuticals and agrochemicals. As with most production facilities, the capital cost of any chemical plant is directly related to its size. Following this argument, it is clearly advantageous to reduce the plant size. In order to reduce the plant size, the intermediate storage is reduced. In most instances, the capacity of intermediate storage is determined heuristically by or using proven rules of thumb. During the operation of batch chemical plants, there is an inherent idleness in the way units are used (they are not used continuously). This idleness can be exploited to reduce the plant size and increase the capital utilisation of process units. A mathematical model was derived and tested in order to take this storage into account using the state sequence network (SSN) process representation in a continuous time framework.

Developing a complete process integration framework for wastewater minimisation in batch processes

The need for industry to produce the smallest possible amount of effluent is greater than ever. This is due to the fact that environmental legislation is becoming even more stringent and freshwater sources are becoming scarcer. This has prompted research into economic means of reducing the amount of wastewater, while still producing the right quality and quantity of the required product. Wastewater minimisation techniques have, in the past, been mainly focused on continuous types of operations. However, due to the nature of the wastewater produced from batch processes, wastewater minimisation cannot be ignored. Relatively few methodologies for wastewater minimisation in batch processes have been presented in the past. Those that have been developed are mainly focused on wastewater characterised by single contaminants and situations where the optimal production schedule is known beforehand. Four novel methodologies have been developed that deal with four different aspects of wastewater minimisation in batch plants. These are multiple-contaminant wastewater, multiple storage opportunities, zero-effluent operation and inherent storage in a batch plant. These methodologies combine to form a complete framework for wastewater minimisation in batch processes. The effectiveness of the methodologies has been demonstrated through a number of illustrative and practical applications.

Energy optimisation in multipurpose batch plants using heat storage

The concept of heat integration in batch chemical plants has been reported in literature for more than a decade. However, most publications tend to advocate direct rather than indirect heat integration in batch chemical processes. Direct heat integration is encountered when both the source and the sink processes have to be active over a common time interval, assuming that the thermal driving forces allow it. On the other hand, indirect heat integration allows the heat integration of processes regardless of the time interval, as long as the source process takes place before the sink process so as to store energy or heat for later use. Nonetheless, the thermal driving forces must still be obeyed. It is, therefore, evident that direct heat integration is more constrained than indirect heat integration. A research project in this regard entails the development of a mathematically rigorous technique for the optimisation of energy use through the exploitation of heat storage in heat-integrated multipurpose batch plants. The storage of heat is effected through the use of a heat transfer fluid.
It is envisioned that the resultant mathematical formulation will exhibit a mixed integer linear programming (MILP) structure, thereby yielding a globally optimal solution for a predefined storage size.

Process integration for efficient utilisation of energy in IGCC plants

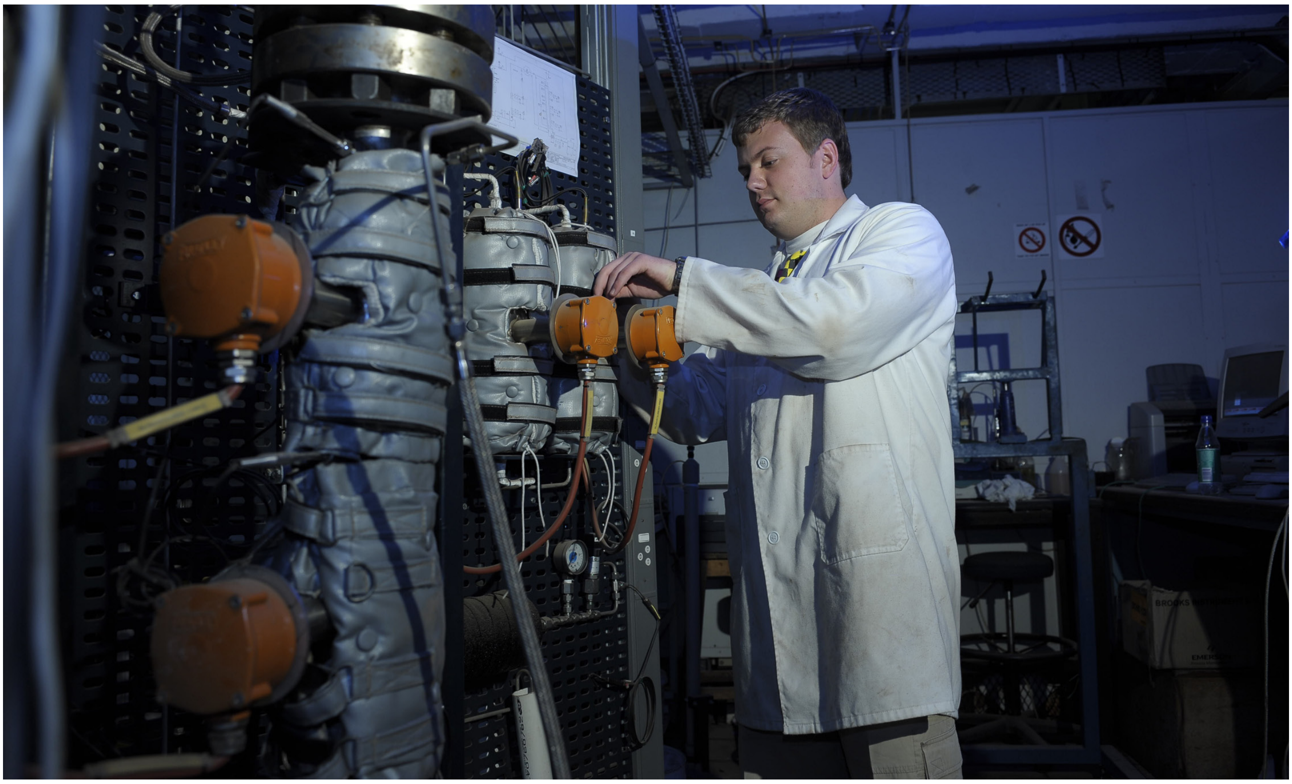
Over the years, coal has gained a reputation as an environmentally destructive energy resource, due to the level of CO_2 emissions associated with it. The main sources of these emissions are coal-fired electricity power generation plants. The other significant source is coal-to-liquids technology, which is becoming even more attractive as an alternative source of energy, due to soaring oil prices. Consequently, this form of contribution to CO_2 emissions is likely to be part of humankind for many years to come. However, the abundance of coal in the seams of the planet, combined with its proven fuel capabilities, makes it very difficult (if not impossible) to simply abandon it as a fuel of choice well into the future. It is, therefore, imperative that more environmentally friendly methods of harnessing coal be developed and implemented on a global scale. The integrated gasification combined cycle (IGCC) is a promising technology in this regard. Although not proven in practice, theoretical investigations have shown that it can achieve overall thermal efficiencies in excess of 60% if optimally designed and operated. The main advantage lies in generating electricity from two sources, steam and gas turbines, using the common coal input. Although this framework is inherently integrated, most of the published work tends to analyse it as a combination of discrete unit operations, thereby resulting in sub-optimality. True optimality of this system can be achieved by analysing it as the comprehensive framework that it truly is, hence the choice of process integration as an optimisation tool.

Recently completed work on the steam side has demonstrated that a process integration-based design is capable of increasing the overall thermal efficiency by almost 4%, based on a coal high-heating value (HHV) of 678.5 MW. This improvement is mainly due to the increase in steam flow rate, which consequently improves the steam turbine electric power output by almost 20% from 121 MWe to slightly more than 144 MWe.
In the current investigation, the sufficiently detailed performance models for the gasifier and the gas turbine are integrated in an elaborate mathematical structure that describes the gas side performance of the IGCC. The aim of the mathematical model is to determine the operating conditions in both the gasifier and the combustion chamber of the gas turbine to yield optimum thermal efficiency. The analysis is based on the fixed thermodynamic properties of the exhaust gas from the gas turbine so as not to disturb the performance of the heat recovery steam generator (HRSG), which is a crucial component of the IGCC.

A process integration method for the optimisation of steam system networks

The use of steam in heat exchanger networks (HENs) can be considerably reduced by the application of heat integration and optimisation with the intention of debottlenecking the steam boiler and indirectly reducing the water requirement. The reduction of steam flow rate in an HEN affects the operation of the steam boiler. By reducing the steam flow rate, the return condensate temperature to the boiler is compromised, which adversely affects the operation of the boiler. A means of maintaining the efficient operation of the boiler, while still reducing the overall steam flow rate to the heat exchanger network, is to reheat the return flow to the boiler to a sufficiently high temperature. One means of achieving this is by utilising the sensible heat from the superheated steam, leaving the boiler to preheat the boiler feed.

This investigation concerns the optimisation and restructuring of all



→ *Research is conducted in the Reactor Engineering Laboratory in the Department of Chemical Engineering.*

steam system heat exchangers using conceptual and mathematical analysis to create a series HEN with the aim of reducing the overall steam flow rate, while maintaining boiler efficiency. Application of this method to a case study involving seven heat exchangers resulted in a 26.3% reduction in steam system flow rate, which renders this a promising concept.

Research collaborations

A number of academic research collaborations are involved in these sustainable process systems engineering projects, including ones with the University of Pannonia, Hungary, the University of Nottingham, Malaysia, the University of Limerick, Ireland, the Universitat Rovira i Virgili, Spain, the De La Salle University, Manilla, Phillipines, the National University of Taiwan, the Indian Institute of Technology, Bombay, India, and the India Institute of Technology, Bombay. Industry partners include African Explosives Limited, Johnson & Johnson (Pty) Ltd, the Council for Scientific and Industrial Research (CSIR), Unilever South Africa and Amalgamated Beverage Industries (ABI).

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