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Editorial

# Recent novel developments in heat integration—total site, trigeneration, utility systems and cost-effective decarbonisation. Case studies waste thermal processing, pulp and paper and fuel cells

## 1. Introduction

The future development of the economy is closely connected with contribution achieved for cleaner production including more efficient utilisation of materials, and energy, the reduction of the negative impacts of these processes upon humans and upon the eco-system.

The series of conferences on "*Process integration, modelling and optimisation for energy saving and pollution reduction*" (PRES) was established originally to address issues relevant to process integration in connection with the thermal efficiency of various processes, but it has now been expanded to focus highly on energy saving and pollution reduction issues. The organisers of the PRES conferences have been delighted to extend conference participation beyond that of industrialised nations and have attracted delegates from less developed countries as well. Since *all people of all nations share just one planet* and many of the environmental pollution issues have global impacts, we must all work together to develop and implement better and cleaner production concepts, policies, tools and technologies to help ensure that we make real progress toward sustainable societies throughout the world.

This is already the fifth Special Issue of the *Applied Thermal Engineering*. The previous issues based upon papers submitted to PRES conferences were published from 2000 through 2004 [1–4]. The PRES conference is also collaborating with other known journals (see e.g. [5–7]), the collaboration with the *ATE* has got the longest tradition and has been mutually greatly appreciated.

The most recent conference, PRES'03, was held outside the European continent for the first time. The PRES organisers were very pleased to accept the invitation from the Canadian Society for Chemical Engineering and Chemical Institute of Canada. PRES'03 was held jointly with the 53rd Canadian Chemical Engineering Conference—CSChE 2003 in Hamilton, Ontario, Canada. The Canadian organisers lead by Andrew Hrymak and Roland Anderson contributed enormously to the success of the PRES conference.

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## 2. Overview of papers included in this issue

For this Special Issue of the *Applied Thermal Engineering,* ten papers representing various aspects of thermal engineering-related inputs are included. The internationality of PRES is reflected partly by the fact that the authors of the selected papers are from ten countries, i.e. Belgium, Brazil, Canada, the Czech Republic, Mexico, Poland, Romania, Sweden, Switzerland, and the United Kingdom. These papers are partitioned into three thematic groups. The first group deals with recent advances in heat integration methodology. The second one focuses upon issues related to heat exchangers while the last group is dedicated to several interesting applications including thermal processing of waste, pulp and paper industry, and fuel cells development.

The first group contains three papers. Paper developed at the CANMET Energy Technology Centre—Varennes, Québec, Canada by M. Sorin and A. Hammache is titled *A new thermodynamic model for shaftwork targeting on total sites* [8]. The paper contributes to an important extension of process integration methodology introduced in this journal years ago [9] that was based on a research from UMIST [10]. The Canadian authors developed a targeting model based on a new thermodynamic insight on cogeneration in general and Rankine cycle in particular. The insight permits to express the ideal shaftwork of a cogeneration unit through the outlet heat load and the difference in Carnot factors between the heat source and heat sink for the given inlet temperature of the heat source. The deviation from the ideal shaftwork to a real one is assessed by using the traditionally turbine isentropic efficiency. Finally, the new model allows targeting fuel consumption, cooling requirement, and shaftwork production with high accuracy and visualising them directly as special segments on the *T–H* diagram.

A modified Site Utility Grand Composite Curve (SUGCC) diagram is proposed and compared to the original SUGCC. The shape of the right hand side of the diagram above the site pinch is the same, however, below the site pinch it is shifted to the left by an amount equal to the shaftwork production below the site pinch. Above the site pinch, VHP consumption is also corrected to account for the shaftwork production above the site pinch that is represented by segments rather than areas on the left hand side of the *T–H* diagram.

The second contribution of the first group of papers is from Institute for Scientific Research, University of Guanajuato, Mexico and Mexican Petroleum Institute. The paper by E. Teopa Calva, M. Picón Núñez and M.A. Rodríguez Toral titled *Thermal integration of trigeneration systems* [11] addresses a further extension of the cogeneration. This technique was first introduced in the early 80s and is commonly used in municipal heating and cooling [12]; nevertheless, it has been gradually used in chemical and petrochemical industries due to the frequent need of these three utilities in process plants [13]. Mexican authors focus on trigeneration schemes where a gas turbine is used as a prime mover for power production and the cooling is generated by a typical compression–refrigeration system. In most applications, a gas turbine will meet either the process power requirements or the heating needs, but it is unlikely that both would be satisfied simultaneously in the most efficient manner. The selection of the gas turbine that minimises the heat losses to the ambient while supplying the required power can be readily accomplished by superimposing the turbine exhaust gas temperature profile to the process streams profile in a *T* vs. Enthalpy curve. This is because the maximum overall efficiency depends on the process heat and power demands and on the shape of the heat demand profile of the process. The use of the thermodynamic model helps to simulate the main components of the system and permits a fast and interactive way to design the optimum trigeneration scheme using the performance data of commercial gas turbines.

The third contribution titled, *Synthesis of industrial utility systems: cost-effective decarbonisation* [14], originates from UK, as a result of joint effort of Department of Process Integration, UMIST and The Tyndall Centre for Climate Change Research (North), by Petar Varbanov, Simon Perry, Jiri Klemeš, and Robin Smith. The production processes on industrial sites normally require large amounts of heating, cooling and power for their operation. Therefore, the optimal synthesis of utility systems is of central interest to engineers in the process industries. Recently, the problem of the global climate change has brought forward the question of reducing significantly the emissions of greenhouse gases into the atmosphere.

In this paper, a new approach is presented for cost-effective de-carbonisation of new utility systems in the process industries. This approach is based on improved models of utility equipment components and on an improved model and procedure for optimal synthesis of utility systems. The utility system supplies steam for heating to site processes. On the other hand, steam can be generated from high-temperature process cooling that is then passed to the steam system. The cooling demands are met by using cooling water, air-cooling or refrigeration. In addition, the utility system needs to satisfy the power demands of the site. There are three important groups of interactions concerning the operation of utility systems. Firstly, it is not likely that the sites will be in power balance; they usually import or export power. Furthermore, the economic conditions such as the market prices of fuels and electricity vary with time. There are also variations in product demands, feedstock compositions, the ambient conditions, etc. The environmental impact of utility systems needs to be integrated into a synthesis model, which is dictated by the need for significant reduction of these emissions. It should be carried out accounting for the economics, since the decisions in industry are driven by profitability.

The second group of papers begins with a contribution from State University of Maringá, Brazil. Authors M.A.S.S. Ravagnani, A.P. Silva, P.A. Arroyo, and A.A. Constantino presented the paper *Heat exchanger network synthesis and optimisation using genetic algorithm* [15]. In the previous few decades, several papers were published on heat exchanger network synthesis. Most of them present techniques using mathematical programming for the synthesis and optimisation tasks.

Recent developments in heat exchanger networks synthesis present some heuristic methods, such as genetic algorithm (GA) and simulated annealing. In this paper, a strategy for the synthesis and optimisation of heat exchanger networks was developed using GA. First of all, the $\Delta T_{\min}$ is optimised using GA jointly with the problem table from the Pinch Analysis. By using the optimum $\Delta T_{\min}$, found in the previous stage, the problem is divided in two different regions, below and above the pinch. Thus, using GA, the optimal networks above and below the pinch are obtained, considering stream splitting as well. Some examples from the literature were solved with the proposed systematic approach, and the results show heat exchanger networks with lower costs than those presented in the literature for the cases studied.

A second heat exchanger-related paper is from Warsaw University of Technology—Plock Campus, Poland. It is authored by Mariusz Markowski and Krzysztof Urbaniec and is titled *Optimal cleaning schedule for heat exchangers in a heat exchanger network* [16]. In process plants incorporating heat exchangers networks for heat recovery, fouling of heat-transfer surfaces hinders correct production activity and increases energy consumption thus giving rise to economic losses. The losses can be reduced if on-line cleaning of heat exchangers is applied. The scheduling of cleaning interventions on the individual exchangers in the HEN can be based on a priori knowledge of the time behaviour of the thermal resistance of fouling.

In this paper, the mathematical model of the influence of fouling on heat exchanger and HEN operation is outlined and an example of its application is presented. Heat exchanger cleaning is postulated to maximise the avoided loss understood as the value of energy recovered if cleaning the HEN, minus the value of energy recovered without HEN cleaning, minus the cost of HEN cleaning. The mathematical formulation of the avoided loss is given and the computational approach to its maximisation is outlined. The example of optimal scheduling of cleaning interventions in a HEN comprising ten heat exchangers is considered and numerical results are presented.

The next paper is the result of a joint effort among researchers from Romania and Belgium, Vasile Lavric, Valentin Pleşu, Jack De Ruyck, it is entitled *Chemical reactors energy integration through virtual heat exchangers—benefits and drawbacks* [17]. The authors are claiming that the main drawback of the Pinch Analysis concept is the fact that it disregards the contribution of the Chemical Reactors Network (CRN) to the total flowsheet entropy generation resulting in a suboptimal solution. The Chemical Reactors Energy Integration (CREI) through Virtual Heat Exchangers emerged and became, during its crystallisation period, an expansion of the classical Pinch Analysis. It allows the CRN to be seen as part of the Heat Exchangers Network, perhaps leading to a better decrease in the total entropy production both through the inclusion of CRN sources and sinks into the HEN topology, and the improvement of the reactors operating conditions, while preserving their performance, in terms of chemical transformation. The benefits and the drawbacks of the proposed Chemical Energy Reactors Energy Integration are illustrated via the analysis of a case study, a two-bed methanol synthesis heat integrated reactor.

The major drawback of the CREI analysis is that with networks larger than two reactors, the virtual hot/cold streams could be completely decoupled form their counterpart chemical process streams, thereby rendering the analysis very difficult if not impossible. The general guideline emerging from combined CREI and PA methodology to examine exothermic processes, is either to use all the lower grade utilities available on the site to preheat as much as possible the reactants toward the reactor's exit temperature and to generate some higher grade utilities with the supplemental enthalpy of reaction, or extract the available reactor's chemical enthalpy at the highest possible temperature, or both. This supplement to the reaction heat is the consequence of the need of keeping the exit reactor's performance unchanged. When it comes to CRN with exothermic and endothermic reactors, the supplemental heat available from the exothermic processes should be used, as much as possible, to compensate the heat needed by the endothermic processes.

A further development should be the integration of the CREI-PA with an economic analyser, to avoid non-economic optima, following the latest developments in this area [18]. The impact of the new trends in heat transfer enhancements should also be considered in developing CREI [19].

The first paper of the third group is dealing with waste. Researchers from the Technical University of Brno—VUT, Institute of Process and Environmental Engineering and EVECO Brno, the Czech Republic—Ladislav Bébar, Petr Martinák, Leoš Havlen, Petr Stehlík, and Jaroslav Oral prepared paper entitled *Thermal processing of waste using gasification* [20]. They assessed plausible ways leading to the reduction of energy requirements for thermal processing of waste by gasification technology. The results of gasification tests with specially prepared waste carried out in an experimental fluidised bed reactor operating at atmospheric pressure served as incipient information. The waste was mostly a mixture of shredded textiles and rubber, with a heat value of 33 MJ/kg, and dosed into the reactor at the rate of 15–22 kg/h. The gasification was carried out within the temperature ranging from 800 °C to 860 °C and in the presence of air entering at stoichiometric ratios between 0.15 and 0.25.

Based on the results of the waste gasification testing, heat and mass balances of the incineration plant with capacity of 10 kt/y of industrial waste were evaluated and the results compared with conditions required in an incineration plant operating under an oxidation regime. It was concluded that by utilising the gasification process for thermal decomposition of waste, a significant reduction of investment and operating costs were achieved due to a lower consumption of high-value auxiliary fuel as well as due to a reduced volume of flue gas produced.

The next two papers look into energy savings in pulp and paper plants from different angles.

The purpose of the first study was to assess the potential of reducing the water consumption for energy saving. A joint team from Sweden and Canada, Ulrika Wising, Thore Berntsson and Paul Stuart, Chalmers University of Technology, Department of Chemical Engineering and Environmental Science, Göteborg, Sweden and the Chair in Process Integration for the Pulp and Paper Industry, École Polytechnique Montreal, Canada, presented paper *The potential for energy savings when reducing the water consumption in a kraft pulp mill* [21]. An existing pulp and paper mill was studied targeting the reduction of water consumption. As a result, an increased potential for energy integration was found. When the hot water consumption of the mill is decreased, the live steam demand of the mill also decreases. By decreasing the hot water consumption, however, the quantity and temperature of available excess heat increases. This excess heat can be used for evaporation, reducing the live steam demand further by up to 1.5 GJ/t.

A Pinch Analysis was successfully completed and, after removing pinch violations, the hot water consumption becomes an unimportant factor. Removing all the pinch violations together with using the remaining excess heat for evaporation yields a significantly larger energy savings for the mill (4.0 GJ/t). From an economic optimum perspective it is probably most profitable to do a combination of reducing water consumption, removing pinch violations, and use the remaining excess heat for evaporation.

The second Pulp and Paper oriented contribution was developed by researchers from Switzerland and Canada. David Brown, François Maréchal, and Jean Paris prepared paper *A dual representation for targeting process retrofit, application to a pulp and paper process* [22]. A method for the analysis of process energy requirements was used to identify the potential process retrofit measures in an integrated pulp and paper mill in an early design stage. The minimum energy requirements (MER) of the process were computed using a dual representation that segregates the thermodynamic requirement of the process from its technological implementation. Energy and exergy recovery opportunities were examined to improve the integration of the utility system to the process. An MILP optimisation targeting method was applied to identify the best energy conversion options and to optimise the production of combined heat and power (CHP). Replacing the steam injections to mixing tanks by heat exchangers would decrease the MER by 10%, and increase the combined production of heat and power by a factor 1.7. Improving the exergy efficiency of the paper drying technology would be more difficult to implement, nevertheless, the results indicate that this could bring an additional 12% gain of electricity cogenerated with no change to the MER.

The dual representation of thermodynamic and technological energy requirements has proved to be a valuable tool for the early stages of process energy analysis. It should be used as a preliminary step in a retrofitting procedure to help identify and assess options prior to further analysis. Pinch Analysis, exergy analysis and optimisation techniques have been combined to define energy targets at the system level expressed in terms of the energy costs rather than energy requirements. The illustration of the method by the analysis of a pulp and paper mill provided an insight into process retrofitting options for reducing the energy penalty and maximising the energy conversion efficiency. Energy saving of 29.7 MW (22%) with an increase of 19.7 MWe in the CHP production has been targeted. In comparison with the technological requirements, replacing the steam injections to whitewater reservoir by heat exchangers would reduce the MER by 4.2 MW and increase the CHP production from 12.7 MWe to 21.9 MWe while incurring an increase of only 5.6 $MW_{LHV}$ in the natural gas consumption. Minimising the exergy losses related to the current paper drying conditions appears to be less attractive since it would only increase the CHP production by 2.9 MWe (12%) with no significant reduction of the fuel consumption. It stresses the importance of analysis of energy requirements for the drying section to justify the different pressure levels at which steam is supplied.

The last paper is from Queen's University, Kingston, Ontario, Canada. Paper *The effect of channel-to-channel gas cross-over on the pressure and temperature distribution in PEM fuel cell flow plates"* [23] have been developed by P.H. Oosthuizen, L. Sun, and K.B. McAuley. The authors studied the air flow in a simplified model of the flow plate and adjacent diffusion layer of a Proton Exchange Membrane fuel cell. The three-dimensional flow and temperature distribution in the flow plate-diffusion layer combination has been numerically studied by writing the governing equations in a dimensionless form and by solving the resultant equations using a commercial software package. As a result of the pressure drop along the flow channel, there can be crossover of air through the porous diffusion layer from one part of the channel to another. The conditions under which this crossover becomes important and the effect this crossover on the pressure distribution in the channel and the temperature distribution in the flow plate has been examined in this study. Attention has been paid to flow plates having a single serpentine channel. Various numbers of flow passes through the plates have been considered. The effects of Reynolds number, relative flow plate material thermal conductivity, dimensionless permeability of the diffusion layer and of flow channel geometry on the channel flow and the plate temperature distribution have been numerically examined and related to air cross-over.

The authors of this paper came to the following conclusions: for the flow patterns considered here, channel-to-channel flow crossover is significant only when the porosity of the diffusion layer exceeds an approximate value of 0.65. Flow crossover does have a significant influence on the pressure variation through the channel, tending to decrease the pressure drop across the channel. The dimensionless conductivity of the flow plate material is the dominant factor in determining the magnitude of the temperature gradients in the flow plate, the crossover having a small influence on these gradients for the conditions here being considered.

## 3. Conclusions

We trust that the papers in this Special Issue of *Applied Thermal Engineering* will be of interest and relevant to a broad range of readers and will bring the PRES Conference series to their attention.

The help of all collaborators and the ISC members [24] is gratefully acknowledged, both for actively contributing to the conference and taking part in the editorial process. A special appreciation is being expressed to all authors for their contribution.

We would like to continue and further develop the mutual collaboration between the *Applied Thermal Engineering* and the PRES conference the series. 7th conference PRES 2004 is held in Prague, the Czech Republic, again jointly with CHISA 2004; 8th PRES'05 jointly with ICheaP-07 in Taormina, Sicily, Italy, 15–18 May 2005.

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