CHEMICAL ENGINEERING TRANSACTIONS
VOL. 57, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš, Laura Piazza, Serafim Bakalis

ISBN 978-88-95608- 48-8; **ISSN** 2283-9216

DOI: 10.3303/CET1757052

Heat Exchanger Network Synthesis Considering Risk Assessment for Entire Network Lifetime

Andreja Nemet*[,a], Jiří J. Klemeš[a], Zdravko Kravanja[b]

[a]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT BRNO, Technická 2896/2, 616 69 Brno, Czech Republic
[b]Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova ulica 17, 2000 Maribor, Slovenia
nemeta@gmail.com

Considering risk assessment at the early-stage of Heat Exchanger Network (HEN) synthesis can significantly contribute to obtaining inherently safer design. The development of quantitative safety metrics at the early stage of design are still at the beginning steps of development. The risk is composed of failure frequency and the severity of the consequences. There are numerous methods for determining the severity of the consequences for a certain deviation event and there are mainly index-based methods for determining the severity when inherent safety is analysed. The failure of frequency, however, is usually assumed as a constant during the entire lifetime. Observing Bathtub curve it can be concluded that different type of failures dominates at different periods during a lifetime. Therefore, considering unified failure frequency during the entire lifetime is quite problematic. The aim of this study is to obtain HEN design that exhibits improved safety during the entire lifetime.
The previously developed mixed-integer nonlinear programming (MINLP) model for HEN synthesis with embedded risk assessment was upgraded to a model that considers the changing failure frequency during the lifetime. A multi-period MINLP model was developed that accounts for different failure rate within each period of the lifetime. At least three periods should be considered (early stage, random and wear out failures). More reliable results regarding HEN design with enhance safety can be obtained by considering the mentioned different failure rates and different aspects of safety (toxicity, flammability, explosiveness). The designs obtained by the enhanced HEN synthesis method are safer and economically reliable.

1. Introduction

Public interest in risk assessment has been continuously increasing over the last three decades, resulting in a need for developing safer and more reliable processes (Marhavilas et al., 2011). The application of safety metrics as a part of the design of several unit operation and chemical processes is still at an early stage of development (Roy et al., 2016). Jung et al. (2010) optimised the placement of a hazardous process unit and other facilities using mixed-integer nonlinear programming considering a risk map in the plant area. Kim et al. (2011) presented an index-based approach to qualitative risk assessment for a hydrogen infrastructure comparing different infrastructure scenarios. Shariff et al. (2012) presented the process stream index (PSI) that enables designers to identify critical streams with high explosion potential in order to indicate critical points in a network regarding explosiveness. A similar study was later conducted for toxic release (Shariff and Zaini, 2013). Chan et al. (2014) combined the inherent safety index with Stream Temperature vs. Enthalpy Plot (STEP) analysis, developed for HEN design resulting in a graphical approach based on heuristics. Liu et al. (2015) presented a step-by-step procedure for risk assessment of heat transfer between different processes in Total Sites, considering direct or indirect heat transfer. Vázquez-Román et al. (2015) presented a mathematical programming approach to determine the optimal layout of facilities considering toxic releases using a cause-effect analysis. Inchaurregui-Méndez et al. (2015) presented a HEN synthesis approach based on inherent safety, where a HEN layout with allocations of hot/cold streams was considered.
The authors previously developed (Nemet et al., 2017) a superstructure approach for HEN design considering safety limits during the synthesis. The heat exchanger failures were considered as an average failure during

Please cite this article as: Nemet A., Klemes J.J., Kravanja Z., 2017, Heat exchanger network synthesis considering risk assessment for entire network lifetime, Chemical Engineering Transactions, 57, 307-312 DOI: 10.3303/CET1757052

lifetime (Nemet et al, 2017). This is a problematic assumption as the failure rate of HE are varying during the lifetime. In general, at least three periods needs to be considered according to the Bathtub curve. In the first period, the early failures have an important role with decreasing tendency over years until it reaches the constant random failure level that is specific in the second period. In the third period, the wear-out failures become the main source of failures that are increasing with any increase of the lifetime until it reaches a non-acceptable level and the operating lifetime of a heat exchanger is termed. Different types of HE have a different shape of Bathtub curve leading to different failure rate in a certain period. The aim of this study was to consider the varying failure rates during the lifetime of different heat exchanger types. The previously developed HEN synthesis model (Nemet et al, 2017) was upgraded to a multi-period mixed-integer nonlinear programming (MINLP) model considering different failure rate within each period.

2. Methodology

A mathematical programming approach was used for HEN synthesis simultaneously considering risk assessment. Nemet et al. (2017) presented an MINLP model, where the risk assessment and different heat exchanger types were considered. The mentioned model has been now upgraded to a multi-period model, where the individual risk is calculated between each hot stream *hp* and cold stream *cp,* for each type of heat exchanger *hx,* for each type of *risk,* within each period *n.* Risk assessment is performed as multiplication of failure rate $f_{hx,n}^{fail}$ and the severity of consequences as described by Uijt de Haag and Ale (2005) when all content of a heat exchanger would be released. The severity is determined as the mass of substance multiplied with factors $f_{hx}^{1}, f_{hx}^{2}, f_{hp}^{3}$. f_{hx}^{1} is a factor that accounts for process installation versus storage installation, f_{hx}^{2} is a factor for the position of the installation, whether it is an outdoor or indoor installation, and f_{hp}^{3} accounts for process conditions, whether the substance is in gas (different range accounting for pressure), liquid or solid phase. The mass of a substance is determined as the area of heat exchange $A_{hp,cp,hx,m=DIRECT}$ divided by area density β_{hx} (resulting in volume) multiplied by the density of a substance in hot ρ_{hp} or cold ρ_{cp} process streams. Eq(1) presented the calculation of individual risk of heat exchanger when the heat exchange is performed directly.

$$R_{hp,cp,hx,m=DIRECT,risk,n}^{HX} = f_{hx,n}^{fail} \cdot \frac{A_{hp,cp,hx,m=DIRECT} \cdot \rho_{hp} \cdot f_{hx}^{1} \cdot f_{hx}^{2} \cdot f_{hp}^{3}}{\beta_{hx} \cdot G_{hp,risk}} +$$

$$f_{hx,n}^{fail} \cdot \frac{A_{hp,cp,hx,m=DIRECT} \cdot \rho_{cp} \cdot f_{hx}^{1} \cdot f_{hx}^{2} \cdot f_{cp}^{3}}{\beta_{hx} \cdot G_{cp,risk}} \quad \forall hp \in HP, cp \in CP, hx \in HX, risk \in RISK, n \in N$$

Eq(2) and Eq(3) presents the calculation of individual risk of two heat exchanger when the heat exchange is performed via intermediate utility, transferring first heat from hot process stream to intermediate utility – Eq(2) and after from intermediate utility to cold process stream - Eq(3).

$$R_{hp,iu,hx,m=INDIRECT,risk,n}^{\mathrm{HX,hot}} = f_{hx,n}^{fail} \cdot \frac{A_{hp,iucold,k,hx,m=INDIRECT}^{\mathrm{hot}} \cdot \rho_{hp} \cdot f_{hx}^{1} \cdot f_{hx}^{2} \cdot f_{hp}^{3}}{\beta_{hx} \cdot G_{hp,risk}} \tag{2}$$

$$\forall hp \in HP, iu \in IU, hx \in HX, risk \in RISK, n \in N$$

$$R_{iu,cp,hx,m=INDIRECT,risk,n}^{\mathrm{HX,cold}} = f_{hx,n}^{fail} \cdot \frac{A_{iu,cp,k,hx,m=INDIRECT}^{\mathrm{cold}} \cdot \rho_{cp} \cdot f_{hx}^{1} \cdot f_{hx}^{2} \cdot f_{cp}^{3}}{\beta_{hx} \cdot G_{cp,risk}} \tag{3}$$

$$\forall iu \in IU, cp \in CP, hx \in HX, risk \in RISK, n \in N$$

The average risk of HEN is determined as the sum of individual heat exchanger risk over periods, divided by the number of periods that is the lifetime t_{LT}.

$$R_{risk}^{HEN} = \left(\sum_{hp} \sum_{cp} \sum_{hx} \sum_{n} R_{hp,cp,hx,m=DIRECT,risk,n}^{HX} + \right. \tag{4}$$

$$\left. \sum_{hp} \sum_{iucold} \sum_{hx} \sum_{n} R_{hp,iucold,hx,m=INDIRECT,risk,n}^{HX,hot} + \sum_{iuhot} \sum_{cp} \sum_{hx} \sum_{n} R_{iuhot,cp,hx,m=INDIRECT,risk,n}^{HX,cold} \right) / t_{LT} \qquad \forall risk \in RISK$$

The safety limits are restricted by setting the upper limits on either the sum of individual risk within a period of all existing heat exchangers or average risk of HEN.

The objective function was set as the incremental net present value, determining differences between the case with and without heat recovery.

$$\Delta W_{ENPV} = W_{ENPV}^{HI} - W_{ENPV}^{NoHI} = -\Delta I + \Delta F_{\mathrm{C}} \cdot \frac{\left(1+r^{\mathrm{disc}}\right)^{t^{\mathrm{LT}}} - 1}{r^{\mathrm{disc}} \cdot \left(1+r^{\mathrm{disc}}\right)^{t^{\mathrm{LT}}}} = -\Delta I + \left(\left(1-r_{\mathrm{T}}\right)\left(c_n^{\mathrm{tot}} - c_n^{\mathrm{OP}}\right) + r_{\mathrm{T}} \frac{\Delta I}{t_{\mathrm{LT}}}\right) \cdot \frac{\left(1+r^{\mathrm{disc}}\right)^{t^{\mathrm{LT}}} - 1}{r^{\mathrm{disc}} \cdot \left(1+r^{\mathrm{disc}}\right)^{t^{\mathrm{LT}}}} \quad (5)$$

The incremental annual cash flow ΔF_{C} after tax (tax rate r_{T}) consists of incremental operating cost, calculated as the difference between the operating cost when no heat integration is performed c_n^{tot} and the optimised operating cost c_n^{OP} , and depreciation, calculated as the incremental investment ΔI divided by HEN lifetime t_{LT}

The r^{disc} is the inflation and interest rate together.

The annual operating cost after optimisation c_n^{OP} is determined as the hot utility consumption Q_n^{HU} multiplied by its price c^{HU} summed up with the cold utility consumption Q_n^{CU} multiplied by its price c^{CU} .

$$c_n^{\mathrm{OP}} = Q_n^{\mathrm{HU}} \cdot c^{\mathrm{HU}} + Q_n^{\mathrm{CU}} \cdot c^{\mathrm{CU}} \quad (6)$$

The depreciation is determined by the sum of fixed cost c_{hx}^{fix} and variable cost c_{hx}^{var} multiplied with the optimal area of direct $A_{hp,cp,hx,st}^{DIR}$ or indirect $A_{hp,cp,hx,st,m}^{HOT}$, $A_{hp,cp,hx,st,m}^{COLD}$ heat transfer divided by the HEN lifetime. Note that *y* stands for existence binary variables.

$$\begin{aligned}\frac{\Delta I}{t_{\mathrm{LT}}} = \Bigg(& \sum_{hp}\sum_{cp}\sum_{st}\sum_{hx} c_{hx}^{fix} \cdot y_{hp,cp,st,hx}^{DIR} + \sum_{hp}\sum_{cp}\sum_{st}\sum_{hx} c_{hx}^{\mathrm{var}} \cdot A_{hp,cp,hx,st}^{DIR} + \\ & \sum_{hp}\sum_{cp}\sum_{st}\sum_{hx}\sum_{m} c_{hx}^{fix} \cdot y_{hp,cp,st,hx,m}^{HOT} + \sum_{hp}\sum_{cp}\sum_{st}\sum_{hx}\sum_{m} c_{hx}^{\mathrm{var}} \cdot A_{hp,cp,hx,st,m}^{HOT} + \\ & \sum_{hp}\sum_{cp}\sum_{st}\sum_{hx}\sum_{m} c_{hx}^{fix} \cdot y_{hp,cp,st,hx,m}^{COLD} + \sum_{hp}\sum_{cp}\sum_{st}\sum_{hx}\sum_{m} c_{hx}^{\mathrm{var}} \cdot A_{hp,cp,hx,st}^{COLD} - I^{ref} \Bigg) / t^{LT}\end{aligned} \quad (7)$$

3. Case study

The presented methodology was applied to an illustrative case study consisting of two hot and three cold streams where the non-integrated part demand is covered by the hot utility and cold utility (cold water) - Table 1. Only stream H1 is flammable. The toxicity risk is determined via lethal concetration LC_{50} that describes the amount of substance that is lethal to 50% of the population of rats within one hour via inhalation. The cost of hot utility was considered at 5.77x10^{-4} k€/kW, while cold utility cost at 7.2 x10^{-5} k€/kW. Annual operating time was 8,500 h/y. The tax rate was assumed at 20 % and the inflation and interest rate together at 7 %. The type of heat exchanger considerably impacts the safety of the HEN, therefore, four different type of HE were considered during HEN synthesis. The data was taken from Soršak and Kravanja (2002) see Table 2. The failure rate was considered for each period separately, the input data for the different type of HE presented in this case study is presented in Figure 1.

Table 1:Input data for streams in the case study

Stream	medium	T^{in}/ K	T^{out}/ K	*CP*/ kW K^{-1}	*Q*/ kW	*h*/ kW/(m^2.K)	LC_{50} (rat,1h,inh)/mg	Q^{expl}/ kJ kg^{-1}
H1	S	1,253	703	19.94	10,967.0	0.62	4,615	878.3
H2	SO_2	877	723	20.30	3,126.2	0.065	2,520	0
C1	TiO_2 xH_2O	529	660	109.70	14,370.7	0.62	1.61	0
C2	TiO_2 xH_2O	373	529	38.6	6,021.6	0.62	1.61	0
C3	SO_2	371	688	14.8	4,691.6	0.065	2,520	0
HU	Hot oil	1,385	1,365			5	-	-
CU	water	300	321			1	-	-

Table 2: Input data for different types of heat exchangers considered

HE type	T_{hx}^{LO} /K	T_{hx}^{UP} /K	A_{hx}^{LO} /m^2	A_{hx}^{UP} /m^2	cf_{hx}/ k€	cv_{hx}/ k€ m^{-2}	Ft	β_{hx}*/m^2 m^{-3}
Double pipe	173.15	873.15	0.25	200	46	2.742	1	80
Plate and frame	248.15	523.15	1	1,200	129.8	0.347	1	1,300
Fixed plate shell and tube	73.15	1,123.15	10	1,000	121.4	0.193	1	720
Shell and tube with U-tubes	73.15	1,123.15	10	1,000	100.9	0.272	0.8	80

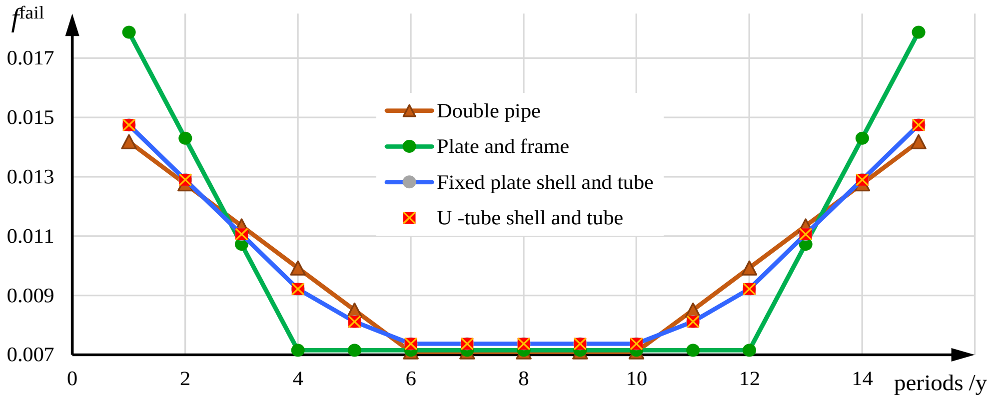

Figure 1: Failure rates of different types of HEs

No risk limit: The HEN design were first determined without risk limits and the risk assessment was recalculated after optimisation. The obtained HEN design is presented in Figure 2. The NPV of this design was 647.533 k€, the investment was 615 k€. Cold utility consumption was 1,100.7 kW, while there was no hot utility requirement. The recalculated average overall risk was 1.284 for toxicity, 0.051 for flammability and 0.090 for explosiveness.

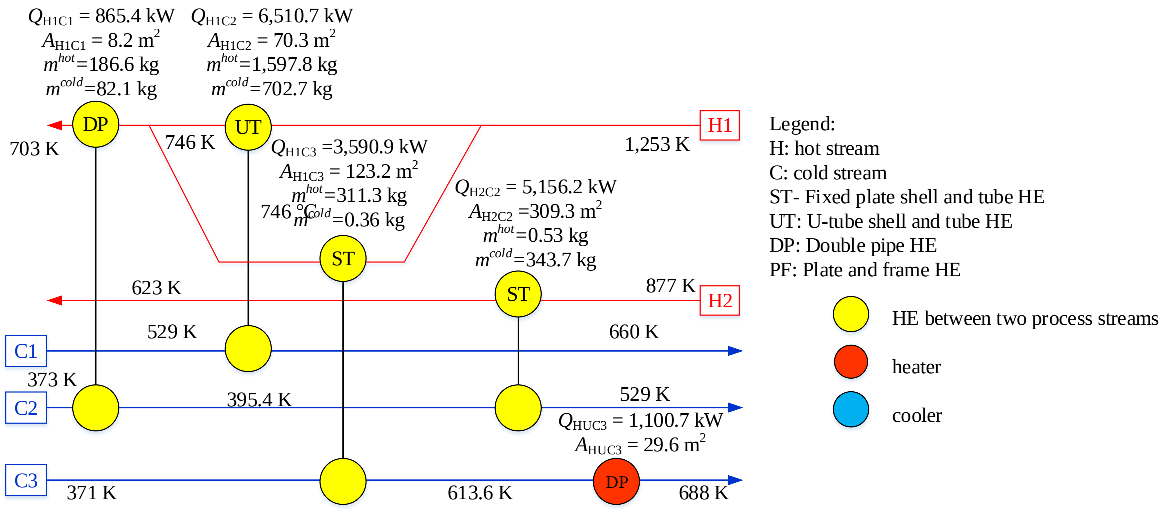

Figure 2: HEN design when no safety limit is set.

Risk limit on risk within each period: The risk limit was halved within each period of entire lifetime compared to recalculated risk of the reference design with no risk assessment. As can be seen in Figure 3, there was a structural change in the network, as the match between H1 and C3 was termed and a new match between H2 and C3 was selected during the optimisation. Additionally, for all the heat transfer the fixed-plate shell-and-tube HE type was applied. The NPV value obtained was similar to the NPV of the reference design, namely 647.432 k€, resulting in 0.101 k€ (0.02%) difference. The heat integration rate remained at the same level and the cold utility consumption was 1,100.7 kW. Table 3 presents the limiting value *G* for each stream when all the heat exchangers were assumed as process equipment (f^1=1), all installed indoor (f^2=0.1). It presents the constant value that is a basis for risk assessment for each match. In the case of no safety limit the HEs of matches H1-C1, H1-C2 and H2-C2 contains higher mass as the limiting value; and they present risky matches. However, when the safety is limited, the HE contain fewer media. This can be seen especially in the case of heat transfer between stream H1 and C1, where the selection of different type of the HE leads to reducing the mass significantly.

Table 3: Limiting value multiplied with the factors for properties of substances and heat exchangers for each stream

Stream	H1	H2	C1	C2	C3
Limiting value [kg]	523.7	300.0	10.0	10.0	300.0

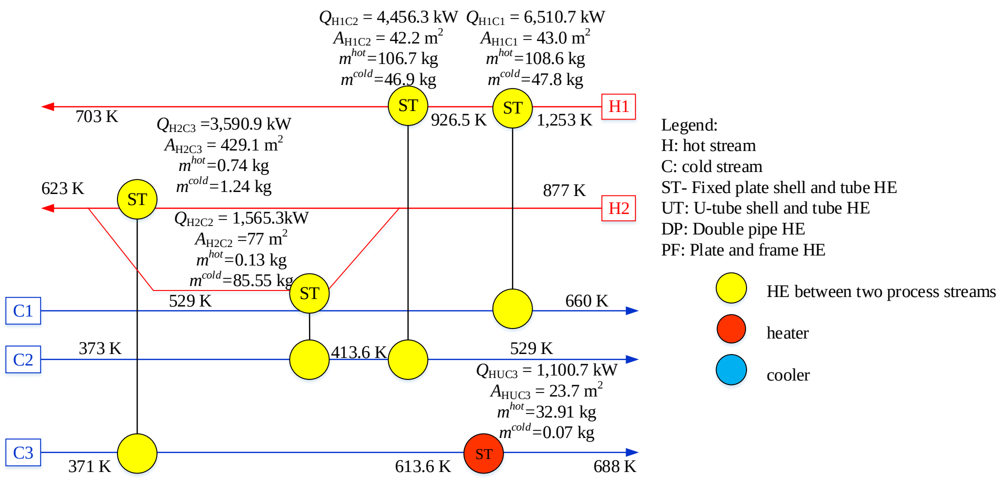

Figure 3: HEN design when the safety limit within each period is halved compared to the initial safety.

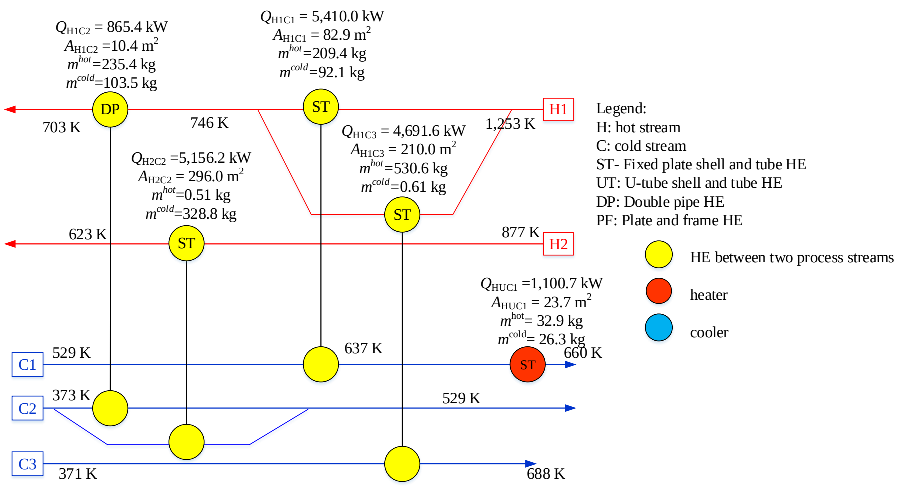

Figure 4: HEN design when the average safety limit is set to average risk limit of design in Figure 3

Risk limit on average risk: The results were compared to HEN design obtained for the same case study using the optimisation model, where the risk assessment is performed with the average failure rate (Figure 4). In order to compare the solutions, the average risk levels were set to the value as recalculated from the previous solution when the safety limit within each period was halved compared to the initial safety (Figure 3). As the comparison of Figure 3 and Figure 4 reveals, the obtained design was not identical. Moreover, the design in Figure 4 is more similar to the reference case study (Figure 2) than to the one of Figure 3. Comparing the mass of substances in HEs it can be seen that they are lower compared to those of the reference case (Figure 2); however, they are higher compared to Figure 3. Those comparisons lead to a conclusion that considering only average failure rate during entire lifetime leads to inaccurate results. As the failure rate of HE are higher at the beginning and ending of the lifetime (Bathtub curve), the heat exchanger areas need to be adapted also to those two critical periods. Those periods in the lifetime are not negligible as they could last also ten years (Rydén, 2003).

4. Conclusion

The methodology for HEN synthesis with simultaneous safety analysis considering different failure rate during lifetime was developed. The safety analysis during the optimisation at an early stage of design leads to inherently safety HENs. It can be concluded that considering average failure rate can lead to underestimated risk leading to larger heat exchangers containing more hazardous material. Therefore, risk limits must be set considering variable failure rates and preferably within each period over a system's lifetime.

Acknowledgments

This research study was financially supported by the EU project "Sustainable Process Integration Laboratory – SPIL" project No. CZ.02.1.01/0.0/0.0/15_003/0000456 funded by the EU "CZ Operational Programme Research and Development, Education", Priority 1: Strengthening capacity for quality research and by the Slovenian Research Agency (programs P2-0032, project L2-7633 and scheme "Spodbujanje mladih doktorjev znanosti" contract number 1547/FKKT-2015).

References

Chan I., Wan Alwi S.R., Hassim M.H., Manan Z.A., Klemeš J.J., 2014, Heat Exchanger Network Design Considering Inherent Safety, Energy Procedia, 61, 2469-2473.

Inchaurregui-Méndez J.A., Vázquez-Román R., Ponce-Ortega J.M., Sam Mannan M., 2015, A Heat Exchanger Networks Synthesis Approach Based on Inherent Safety, Journal of Chemical Engineering Research Updates, 2, 22-29.

Jung S., Ng D., Laird C.D., Mannan M.S., 2010, A new approach for facility siting using mapping risks on a plant grid area and optimization, Journal of Loss Prevention in the Process Industries, 23, 821-830.

Kim J., Lee Y., Moon I., 2011, An index-based risk assessment model for hydrogen infrastructure, International journal of hydrogen energy, 36, 6387-6398.

Liu X., Klemeš J.J., Varbanov P.S., Qian Y., Yang S., 2015, Safety issues consideration for direct and indirect heat transfer on total sites, Chemical Engineering Transactions, 45, 151-156 DOI:10.3303/CET1545026

Marhavilas P.K., Koulouriotis D., Gemeni V., 2011, Risk analysis and assessment methodologies in the work sites: On a review, classification and comparative study of the scientific literature of the period 2000-2009, Journal of Loss Prevention in the Process Industries, 24, 477-523.

Nemet A., Klemeš J.J., Kravanja Z., 2017, Synthesis of Safer Heat Exchanger Networks, Chemical Engineering Transaction 56.

Roy N., Eljack F., Jiménez-Gutiérrez A., Zhang B., Thiruvenkataswamy P., El-Halwagi M., Sam Mannan M., 2016, A review of safety indices for process design, Current Opinion in Chemical Engineering, 14, 42-48.

Rydén L., 2003, Field reliability of plate heat exchangers in oil and gas processes - a market perspective, <www.pm.lth.se/fileadmin/pm/Exjobb/Exjobb_2003/Exjobbny.pdf>, accessed 9.1.2017

Shariff A.M., Leong C.T., Zaini D., 2012, Using process stream index (PSI) to assess inherent safety level during preliminary design stage, Safety Science, 50 (4) 1098–1103.

Shariff A.M., Zaini D., (2013) Inherent risk assessment methodology in preliminary design stage: A case study for toxic release, Journal of Loss Prevention and the Process Industries, 26(4), 605-613.

Soršak A., Kravanja Z., 2002, Simultaneous MINLP synthesis of heat exchanger networks comprising different exchanger types, Computers and Chemical Engineering, 26, 599-615.

Uijt de Haag P.A.M., Ale B.J.M., 2005, Guidelines for qualitative risk assessment, CPR18E, Gevaarlijke Stoffen, Hague, The Netherland.

Vázques-Román R., Inchaurregue-Méndez J.A., Sam Mannan M., 2015, A grid-based facilities allocation with safety and optimal heat exchanger network synthesis, Computers and Chemical Engineering, 80, 92-100.