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A model for simultaneous synthesis of flexible heat exchanger networks with heat storage - CASE: Oxyfuel power production

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A model for simultaneous synthesis of flexible heat exchanger networks with heat storage - CASE: Oxyfuel power production

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Abstract

In this work a model for synthesizing flexible heat exchanger networks is presented. The model incorporates also the possibility of including heat storage. The model is based on the simultaneous stage-wise superstructure called Synheat, but due to the existence of heat storage and unit by-passes, the energy balances after each stage are nonlinear functions. This naturally increases the complexity of solving the model, but on the other hand no isothermal mixing assumption is necessary. The model is tested in a case study that is an oxyfuel power plant producing both heat for a district network and electricity while capturing CO_2 from the flue gases. In the case study only one stream is allowed to be stored. The results applying the model show that an annual investment potential of 3.4 M$ is possible if a single stream is allowed to be stored.

Keywords: heat exchanger network synthesis, Synheat model, flexibility, MINLP, oxyfuel, CCS

1. Introduction

Heat exchanger network synthesis (HENS) has been an active research area for more than 40 years. This is mainly due to its importance in cost-efficiently achieving energy savings in industrial processes. A lot of different tools and methods have been presented to solve the HENS problem. The objective for most of the research done on the heat exchanger network synthesis problems can be formulated as follows:

> *The objective is to design a heat exchanger network that minimises the total annualised cost, given sets of hot streams, cold streams, hot utilities and cold utilities. Each hot and cold stream has a specific heat capacity flowrate, a start- and target temperature.*

Sometimes the formulation above needs to be broadened to take into account that specific heat capacity flowrates, start- and target temperatures or heat transfer coefficients of streams may vary during time. In this case an additional objective in designing the heat exchanger network is flexibility of the network. Flexibility is hard to model and it basically is design dependent. It is also a relative measure meaning that it is measured relatively between different designs and hence can not be measured directly. Thus developing flexible heat exchanger networks is an important task and for this reason a lot of work has been done on this field. One of the first ones studying this problem was Floudas and Grossmann (1986), who developed a multi-period version of the mixed integer linear programming (MILP) transshipment model that accounts for the changes in pinch points and utility requirement at each time period. In their systematic procedure network configurations that require minimum utility cost for each period of operation and involve the fewest number of units can be found. Floudas and Grossmann (1987) developed an optimization method where the problem is decomposed into two stages: (i) prediction of matches (ii) derivation of the network configuration. At each stage, synthesis techniques are combined with a flexibility analysis to test the feasibility of operation

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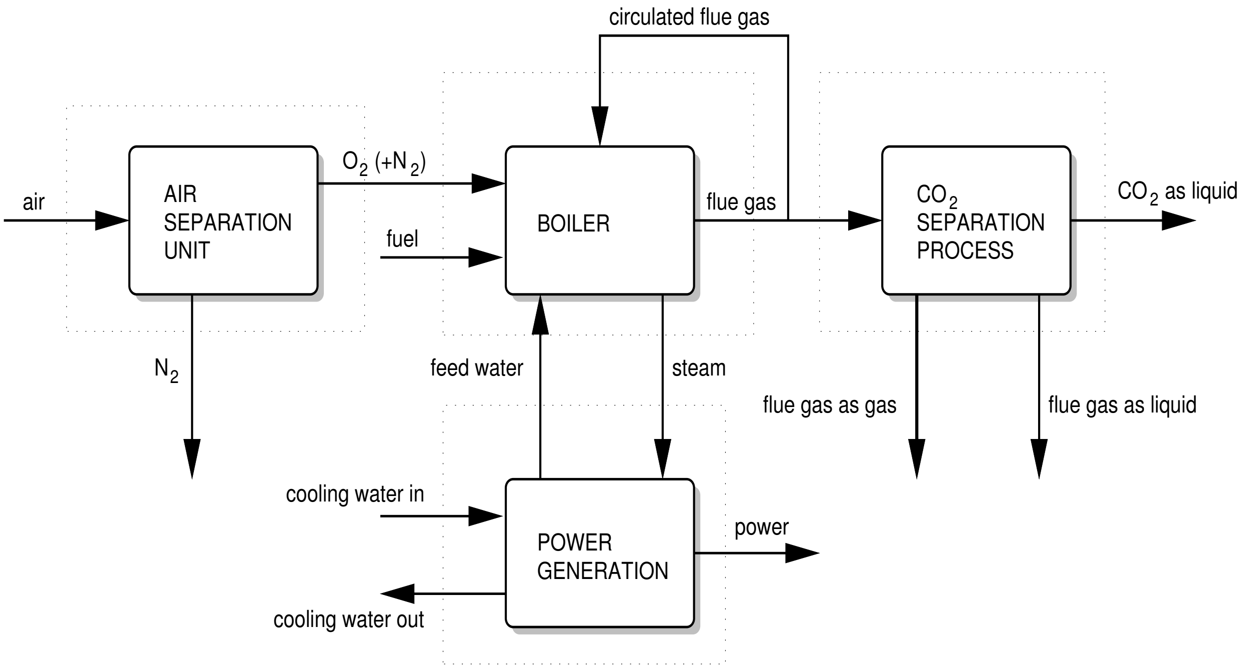

Figure 1: Oxyfuel power production process

of the design over the specified range of the uncertain parameters. Tantimuratha et al. (2001) presented a conceptual tool to address the flexibility and operability objectives for heat exchanger networks. In the approach a screening model to accommodate for the flexibility considerations ahead of design was presented. Aaltola (2002) presented a systematic framework that is based on a multiperiod MINLP model of Yee and Grossmann (1990) for generating flexible heat exchanger networks over a specified range of variations in the flow rates and temperatures of the streams. In the framework feasibility was tested after the network generation using a feasibility model. Konukman et al. (2002) presented a non-iterative, superstructure-based, simultaneous-MILP formulation for HENS synthesis where predefined flexibility targets are included in HENS. In their approach only source-stream temperatures are considered to be the uncertain input parameters in order to keep the convexity assumption needed in their approach. Verheyen and Zhang (2006) made modifications to the work of Aaltola (2002) including the use of maximum area per period in the area cost calculation of the MINLP objective function, and the removal of slack variables and weighed parameters from the existing NLP improvement model.

In this work the objective is to increase the operational flexibility of heat exchanger networks cost-efficiently by using by-passes and heat storage in designing the heat exchanger network. The novelty in the model is that heat storage are used also in continuous processes. Thus heat can be stored in time periods when heat is needed less or external parameters like electricity cost encourage to utilize the heat in a more efficient way. This type of a situation occurs in combined heat and power oxyfuel process simultaneously producing electricity, heat for a district heating network and capturing CO_2 from the process. Oxyfuel power production is one of the first-generation carbon and capture technologies. The idea is to use oxygen instead of air in combustion. Thus the CO_2 concentration level in the flue gas increases substantially compared to air burning and capturing the CO_2 becomes easier. As a drawback the separation of oxygen from air is a very electricity consuming process. In Figure 1 is given a general description of an oxyfuel power process. As can be seen from the figure typically part of the flue gas is recycled back to the combustion unit in order to keep the temperatures in the combustion chamber close to the ones in air combustion.

The rest of this paper is organized as follows. In Section 2 the model is presented. Additionally the special case-ralated equations of the oxyfuel power process are given in Section 2. In Section 3 the parameters,

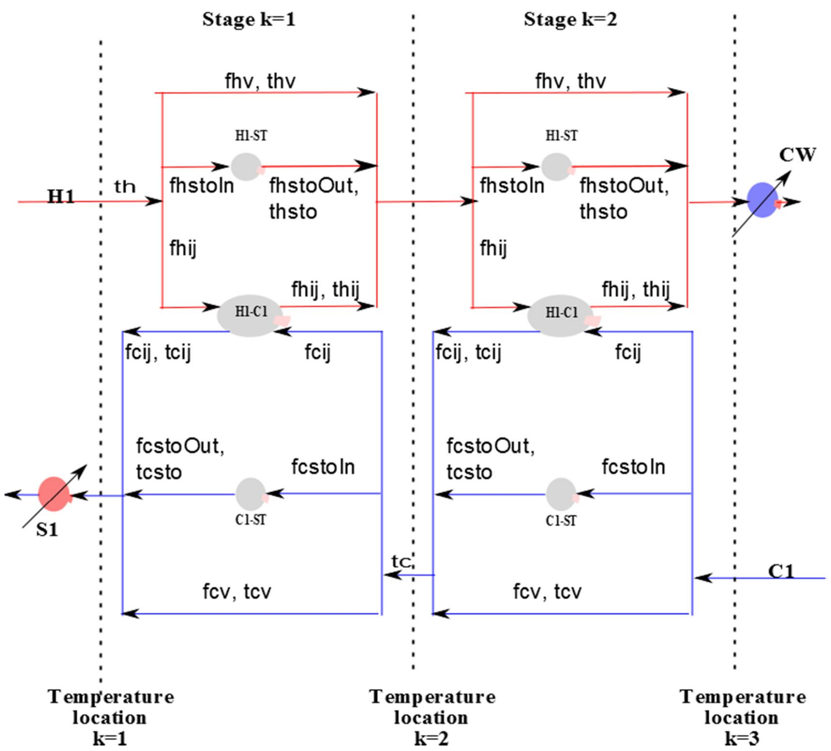

Figure 2: Superstructure for two stages, one heat streams and one cold stream

assumptions and results of applying the model in the case-study are presented. Finally in Section 4 the major conclusions are made.

2. Model

This section presents the model for synthesis of flexible heat exchanger networks.

In the model a well-known superstructure for heat exchanger networks called Synheat Yee and Grossmann (1990) is used as a base for generating different heat exchanger networks. Special for this model presented model is that in addition to normal process stream to process stream heat exchangers and process stream to utility heat exchangers, additionally there is a option for storing heat of a process stream in heat storage and by-passing an existing heat exchanger or storage. This way the heat exchanger can operate flexibly at different stream mass-flows and temperatures i.e. at different load points. This clear benefit does not come without drawbacks. Differently from the basic Synheat model here the stage exit temperatures are not isothermal anymore and hence the equations describing the mixing of different split flows are non-linear and hence harder to solve. Additionally the increase in the number of different options for combining the different equipment increases the complexity of the model.

The heat storage is assumed to operate as a mass storage equipment, meaning that the part of the process flow that enters the storage stays there before it is withdrawn from the storage. So the part of the process stream that enters the storage in a stage is not available for use in following stages during that operational time. The assumption is that no heat is lost in the storage.

Figure 2 presents an example of the superstucture of a model having one hot stream and one cold stream in two stages.

Index	*Description*
i	hot process stream
j	cold process stream
k	temperature location in superstucture (1,...,NOK+1)
p	time period
hu	hot utility
cu	cold utility

Table 1: Indexes needed in model

Set	*Description*
I	$= \{i \,\vert\, i$ is a hot process stream$\}$
J	$= \{j \,\vert\, j$ is a cold process stream$\}$
HU	$= \{hu \,\vert\, hu$ is a hot utility$\}$
CU	$= \{cu \,\vert\, cu$ is a cold utility$\}$
ST	$= \{k \,\vert\, k$ is a stage and temperature location in superstucture$\}$
P	$= \{p \,\vert\, p$ is an time interval$\}$

Table 2: Sets needed in models

2.1. Indexes, sets, parameters and variables in the models

This section describes the sets, parameters and variables needed in all four models of the method. Indexes are given in Table 1, sets in Table 2, parameters in Table 3, positive variables in Table 4, binary variables in Table 5 and unrestricted variables in Table 6.

2.2. Model equations

In this section the equations describing the model are presented.

2.2.1. Objective function

Equations 1 provides the objective function that is minimized. Issues considered are the fixed and size-dependent cost of units, the utility costs and the cost of electricity produced or consumed in steam turbines and compressors in the oxyfuel power production process. Important is to note that no investment costs are related to the storage. This way the maximum allowed investment for storage can be compared to the situation where no storage is allowed.

Parameter	*Description*
$THIN$	Starting temperature of hot stream
$THOUT$	End temperature of hot stream
$TCIN$	Starting temperature of cold stream
$TCOUT$	End temperature of cold stream
$THUIN$	Starting temperature of hot utility
$THUOUT$	End temperature of hot utility
$TCUIN$	Starting temperature of cold utility
$TCUOUT$	End temperature of cold utility
ECH	Heat content of hot stream
ECC	Heat content of cold stream
HC	Stream-individual film coefficient of cold stream
HH	Stream-individual film coefficient of hot stream
HCU	Stream-individual film coefficient of cold utility
HHU	Stream-individual film coefficient of hot utility
$UNITC$	Fixed cost of a heat exchanger
$HUCOST$	Cost of hot utility
$CUCOST$	Cost of cold utility
$ACOEFF$	Cost parameter for area
β	Scale-of-economics parameter for area
$GAMMA$	Upper bound of driving force
$GAMMAI$	Upper bound of driving force
$GAMMAJ$	Upper bound of driving force
$GAMMAHSTO$	Upper bound of driving force
$GAMMACSTO$	Upper bound of driving force
M	Big number
Q^{max}	Maximum possible heat exchange
DT^{max}	Maximum temperature difference
T_{mapp}	Maximum temperature difference
NOK	Number of stages
$TIME$	Time in hours in each time interval
$QMAX$	Maximum storage size
QDD	District heating load

Table 3: Parameters in models

Positive variable	*Description*
th	Temperature of hot stream entering stage
tc	Temperature of cold stream leaving stage
$thij$	Temperature of hot stream after process heat exchanger
$tcij$	Temperature of cold stream after process heat exchanger
thv	Temperature of hot stream in bypass
tcv	Temperature of cold stream in bypass
$thsto$	Temperature of hot stream in hot stream storage
$tcsto$	Temperature of cold stream in cold stream storage
dt	Temperature difference between hot and cold stream
$dtcu$	Temperature difference between hot stream and cold utility
$dthu$	Temperature difference between cold stream and hot utility
fhI	Heat capacity flowrate of hot stream in
fhO	Heat capacity flowrate of hot stream out
fcI	Heat capacity flowrate of cold stream in
fcO	Heat capacity flowrate of cold stream out
$fhij$	Portion of hot stream entering process heat exchanger
$fcij$	Portion of cold stream entering process heat exchanger
fhv	Portion of hot stream entering bypass
fcv	Portion of cold stream entering bypass
$fhstoin$	Portion of hot stream entering storage
$fcstoin$	Portion of cold stream entering storage
$fhstoout$	Portion of hot stream exiting storage
$fcstoout$	Portion of cold stream exiting storage
$fhin$	Heat capacity flowrate of hot stream entering stage
$fhout$	Heat capacity flowrate of hot stream exiting stage
$fcin$	Heat capacity flowrate of cold stream entering stage
$fcout$	Heat capacity flowrate of cold stream exiting stage
$fhstop$	Amount of hot storage in time interval
$fcstop$	Amount of cold storage in time interval
$lmtdij$	Logarithmic temperature difference
$lmtdjut$	Logarithmic temperature difference
$lmtdiut$	Logarithmic temperature difference
$qijk$	Heat exchanged between process streams
qc	Heat exchanged between hot stream and cold utility
qh	Heat exchanged between cold stream and hot utility
$qistoI$	Heat into hot storage
$qistoO$	Heat from hot storage
$qjstoI$	Heat into cold storage
$qjstoO$	Heat from hot storage
$aijk$	Heat exchanger area
$aicu$	Heat exchanger area
$ajhu$	Heat exchanger area
$vhsto$	Volume of hot storage
$vcsto$	Volume of cold storage
$qhLevel$	Level of hot storage
$qcLevel$	Level of cold storage
$wTurb$	Electricity produced in steam turbines
$wTurb$	Electricity produced in steam turbines
$wAsu$	Electricity consumed in Air Separation Unit
$wCO2$	Electricity consumed in CO2 Separation Unit
pEl	Price of electricity

Table 4: Positive variables in models

Binary variable	*Description*
z	Existence of a match
zcu	Existence cold utility heat exchanger
zhu	Existence hot utility heat exchanger
$zisto$	Existence of hot storage
$zjsto$	Existence of cold storage

Table 5: Binary variables in models

Free variable	*Description*
$cost$	Objective value

Table 6: Unrestricted variables in models

$$\begin{aligned} min cost = 0.000001 \cdot (&unitc \cdot \sum_{p,i,j,st} z_{p=1,i,j,st} \\ &+ unitc \cdot \sum_{p,i} zcu_{p=1,i} \\ &+ unitc \cdot \sum_{p,j} zhu_{p=1,st} \\ &+ unitc \cdot \sum_{p,i,st} zisto_{p=1,i,st} \\ &+ unitc \cdot \sum_{p,j,st} zjsto_{p=1,j,st} \\ &+ ACOEFF \cdot \sum_{p,i,j,st} aijk^{\beta}_{p=1,i,j,st} \\ &+ ACOEFF \cdot \sum_{p,i,st} aicu^{\beta}_{p=1,i,st} \\ &+ ACOEFF \cdot \sum_{p,j,st} ajhu^{\beta}_{p=1,j,st} \\ &+ \sum_{p,j} TIME_p \cdot qh_{p,j} \cdot HUCOST \\ &+ \sum_{p,i} TIME_p \cdot qc_{p,i} \cdot CUCOST \\ &+ 8760 \cdot \sum_{p} TIME_p \cdot wAsu_p \cdot 0.001 \cdot pEl_p \\ &+ 8760 \cdot \sum_{p} TIME_p \cdot wCO2_p \cdot 0.001 \cdot pEl_p \\ &- 8760 \cdot \sum_{p} TIME_p \cdot wTurb_p \cdot 0.001 \cdot pEl_p), \ p \in P, j \in j, st \in ST \end{aligned} \tag{1}$$

2.2.2. Heat balance of streams

Equations 2 and 2 give the overall heat balance of hot and cold streams, respectively. A stream can exchange heat with a another process stream, a utility stream or it can be fully or partly directed to heat storage.

$$thin_{p,i} \cdot fhI_{p,i} - thout_{p,i} \cdot fhO_{p,i} = \sum_{j,st} qijk_{p,i,j,st} + qc_{p,i} + \sum_{st} qistoI_{p,i,st} - \sum_{st} qistoO_{p,i,st} \ , \ p \in P, i \in I, st \in ST \tag{2}$$

$$tcout_{p,j} \cdot fcO_{p,i} - tcin_{p,j} \cdot fcI_{p,j} = \sum_{i,st} qijk_{p,i,j,st} + qh_{p,j} + \sum_{st} qjstoI_{p,j,st} - \sum_{st} qjstoO_{p,j,st} \ , \ p \in P, j \in j, st \in ST \tag{3}$$

2.2.3. Mass balance of streams

Equations 4 and 5 give the overall mass of hot and cold streams, respectively.

$$fhI_{p,i} \sum_{k} + fhstoIN_{p,i,k} = fhO_{p,i} + \sum_{k} fhstoOUT_{p,i,st} \ , \ p \in P, i \in I, k \in ST \tag{4}$$

$$fcI_{p,j} \sum_{k} + fcstoIN_{p,j,k} = fcO_{p,j} + \sum_{k} fcstoOUT_{p,j,st} \ , \ p \in P, i \in I, st \in ST \tag{5}$$

2.2.4. Stage hot stream energy balance

Equations 6 to 10 provide the heat balance of a hot stream in a stage.

$$fhIN_{p,i,k} \cdot th_{p,i,k} - fhOUT_{p,i,k} \cdot th_{p,i,k+1} = \sum_{j} qijk_{p,i,j,k} + qistoI_{p,i,k} - qistoO_{p,i,k} \ , \ p \in P, i \in I, j \in J, k \in ST \tag{6}$$

$$fhOUT_{p,i,k} \cdot th_{p,i,k+1} = \sum_{j} fhijk_{p,i,j,k} \cdot thij_{p,i,j,k} + fhv_{p,i,k} \cdot thv_{p,i,k} + fhstoOUT_{p,i,k} \cdot thsto_{p,i,k} \ , \ p \in P, i \in I, j \in J, k \in ST \tag{7}$$

$$qijk_{p,i,j,k} = fhij_{p,i,j,k} \cdot (th_{p,i,k} - thij_{p,i,j,k}) \ , \ p \in P, i \in I, j \in J, k \in ST \tag{8}$$

$$qistoI_{p,i,k} = fhstoIN_{p,i,k} \cdot thsto_{p,i,k} \ , \ p \in P, i \in I, k \in ST \tag{9}$$

$$qistoO_{p,i,k} = fhstoOUT_{p,i,k} \cdot thsto_{p,i,k} \ , \ p \in P, i \in I, k \in ST \tag{10}$$

2.2.5. Stage cold stream energy balance

Equations 11 to 15 provide the heat balance of a cold stream in a stage.

$$fcIN_{p,j,k} \cdot tc_{p,j,k} - fcOUT_{p,j,k} \cdot tc_{p,i,k+1} = \sum_{i} qijk_{p,i,j,k} + qjstoI_{p,j,k} - qjstoO_{p,j,k} \ , \ p \in P, i \in I, j \in J, k \in ST \tag{11}$$

$$fcIN_{p,j,k} \cdot tc_{p,j,k} = \sum_{i} fcijk_{p,i,j,k} \cdot tcij_{p,i,j,k} + fcv_{p,j,k} \cdot tcv_{p,j,k} + fcstoOUT_{p,j,k} \cdot tcsto_{p,j,k} \ , \ p \in P, i \in I, j \in J, k \in ST \tag{12}$$

$$qijk_{p,i,j,k} = fcij_{p,i,j,k} \cdot (tcij_{p,i,j,k} - tc_{p,j,k+1}) \ , \ p \in P, i \in I, j \in J, k \in ST \tag{13}$$

$$qjstoI_{p,j,k} = fcstoIN_{p,j,k} \cdot tcsto_{p,j,k} \ , \ p \in P, j \in J, k \in ST \tag{14}$$

$$qjstoO_{p,j,k} = fcstoOUT_{p,j,k} \cdot tcsto_{p,j,k} \ , \ p \in P, j \in j, k \in ST \tag{15}$$

2.2.6. Stage hot stream mass balance

Equations 16 to 20 provide the mass balance of a hot stream in a stage.

$$fhIN_{p,i,k} = \sum_{j} fhij_{p,i,j,k} + fhv_{p,i,k} + fhstoIN_{p,i,k} \ , \ p \in P, i \in I, k \in ST \tag{16}$$

$$fhOUT_{p,i,k} = \sum_{j} fhij_{p,i,j,k} + fhv_{p,i,k} + fhstoOUT_{p,i,k} \ , \ p \in P, i \in I, k \in ST \tag{17}$$

$$FHI_{p,i} = fhIN_{p,i,k} \ , \ p \in P, i \in I, k \in ST \tag{18}$$

$$FHO_{p,i} = fhOUT_{p,i,k} \ , \ p \in P, i \in I, k = 1 \in ST \tag{19}$$

$$fhOUT_{p,i,k} = fhIN_{p,i,k+1} \ , \ p \in P, i \in I, k = NOK + 1 \in ST \tag{20}$$

2.2.7. Stage cold stream mass balance

Equations 11 to 25 provide the mass balance of a cold stream in a stage.

$$fcIN_{p,j,k} = \sum_{i} fcij_{p,i,j,k} + fcv_{p,j,k} + fCstoIN_{p,j,k} \ , \ p \in P, j \in J, k \in ST \tag{21}$$

$$fcOUT_{p,j,k} = \sum_{i} fcij_{p,i,j,k} + fcv_{p,j,k} + fcstoOUT_{p,j,k} \ , \ p \in P, j \in J, k \in ST \tag{22}$$

$$FCI_{p,j} = fcIN_{p,j,k} \ , \ p \in P, j \in J, k = NOK + 1 \in ST \tag{23}$$

$$FCO_{p,j} = fcOUT_{p,j,k} \ , \ p \in P, j \in J, k = 1 \in ST \tag{24}$$

$$fcOUT_{p,j,k} = fcIN_{p,j,k} \ , \ p \in P, j \in J, k \in ST \tag{25}$$

2.2.8. Stage temperatures

Equations 26 to 33 provide temperatures of subflows of a stream in a stage.

$$th_{p,i,k} = thv_{p,i,k} \ , \ p \in P, i \in I, k \in ST \quad (26)$$
$$thij_{p,i,j,k} \leq th_{p,i,k} \ , \ p \in P, i \in I, j \in J, k \in ST \quad (27)$$
$$tc_{p,j,k} = tcv_{p,j,k} \ , \ p \in P, j \in J, k \in ST \quad (28)$$
$$tcij_{p,i,j,k} \geq tc_{p,i,k} \ , \ p \in P, i \in I, j \in J, k \in ST \quad (29)$$
$$THIN_{p,i} = th_{p,i,k} \ , \ p \in P, i \in I, k = 1 \in ST \quad (30)$$
$$THOUT_{p,i} \leq th_{p,i,k} \ , \ p \in P, i \in I, k = NOK + 1 \in ST \quad (31)$$
$$TCIN_{p,j} = tc_{p,j,k} \ , \ p \in P, j \in J, k = NOK + 1 \in ST \quad (32)$$
$$TCOUT_{p,j} \geq tc_{p,j,k} \ , \ p \in P, j \in J, k = 1 \in ST \quad (33)$$

2.2.9. Utility consumption

Equations 34 and 35 provide cold and hot utility consumption.

$$fhOUT_{p,i,k} \cdot (th_{p,i,k} - THOUT_{p,i}) = qc_{p,i} \ , \ p \in P, i \in I, k = NOK + 1 \in ST \quad (34)$$
$$fcIN_{p,j,k} \cdot (TCOUT_{p,j} - tc_{p,j,k}) = qh_{p,j} \ , \ p \in P, j \in J, k = 1 \in ST \quad (35)$$

2.2.10. Matches

Equations 36 to 42 are used in defining how much heat can be exchanged in heat exchangers and heat storage. If now heat exchanger or storage is built, naturally no heat can be exchanged or stored.

$$qijk_{p,i,j,k} - min(ECH_{p,i}, ECC_{p,j}) \cdot z_{p,i,j,k} \leq 0 \ , \ p \in P, i \in I, j \in J, k \in ST \quad (36)$$
$$qc_{p,i} - ECH_{p,i} \cdot zcu_{p,i} \leq 0 \ , \ p \in P, i \in I \quad (37)$$
$$qh_{p,j} - ECC_{p,j} \cdot zhu_{p,j} \leq 0 \ , \ p \in P, j \in J \quad (38)$$
$$qistoI_{p,i,k} - ECH_{p,i} \cdot zisto_{p,i,k} \leq 0 \ , \ p \in P, i \in I, k \in ST \quad (39)$$
$$qistoO_{p,i,k} - ECH_{p,i} \cdot zisto_{p,i,k} \leq 0 \ , \ p \in P, i \in I, k \in ST \quad (40)$$
$$qjstoI_{p,j,k} - ECC_{p,j} \cdot zjsto_{p,j,k} \leq 0 \ , \ p \in P, j \in J, k \in ST \quad (41)$$
$$qjstoO_{p,j,k} - ECC_{p,j} \cdot zjsto_{p,j,k} \leq 0 \ , \ p \in P, j \in J, k \in ST \quad (42)$$

2.2.11. Temperature differences

Equations 43 to 46 provide correct temperature differences in different heat exchangers.

$$dt_{p,i,j,k} \leq th_{p,i,k} - tcij_{p,i,j,k} + GAMMA_{p,i,j} \cdot (1 - z_{p,i,j,k}) \ , \ p \in P, i \in I, j \in J, k \in ST \quad (43)$$
$$dt_{p,i,j,k+1} \leq thij_{p,i,j,k} - tc_{p,j,k+1} + GAMMA_{p,i,j} \cdot (1 - z_{p,i,j,k}) \ , \ p \in P, i \in I, j \in J, k \in ST \quad (44)$$
$$dthu_{p,j} = THUOUT - tc_{p,j,k} \ , \ p \in P, j \in J, k = 1 \in ST \quad (45)$$
$$dtcu_{p,i} = th_{p,i,k} - TCUOUT \ , \ p \in P, i \in I, k = NOK + 1 \in ST \quad (46)$$

2.2.12. Logarithmic mean temperature differences

Equations 47 to 49 provide the logarithmic temperature differences in different heat exchangers.

$$lmtdij_{p,i,j,k} = dt_{p,i,j,k} \cdot dt_{p,i,j,k+1} \cdot (\frac{dt_{p,i,j,k} + dt_{p,i,j,k+1}}{2})^{\frac{1}{3}} \ , \ p \in P, i \in I, j \in J, k \in ST \quad (47)$$
$$lmtdjut_{p,j} = (THUIN - TCOUT_{p,j}) \cdot dthu_{p,j} \cdot (\frac{(THUIN - TCOUT_{p,j}) + dthu_{p,j}}{2})^{\frac{1}{3}} \ , \ p \in P, j \in J, \quad (48)$$
$$lmtdiut_{p,i} = (THOUT_{p,i} - TCIN) \cdot dtcu_{p,i} \cdot (\frac{(THOUT_{p,i} - TCUIN) + dtcu_{p,i}}{2})^{\frac{1}{3}} \ , \ p \in P, i \in I, \quad (49)$$

2.2.13. Areas

Equations 50 to 52 provide the areas of different heat exchangers.

$$aijk_{p,i,j,k} \geq \frac{qijk_{p,i,j,k} \cdot (\frac{1}{HH_i} + \frac{1}{HC_j})}{lmtdij_{p,i,j,k}} \ , \ p \in P, i \in I, j \in J, k \in ST \tag{50}$$

$$aicu_{p,i,k} \geq \frac{qc_{p,i} \cdot (\frac{1}{HH_i} + \frac{1}{HCU})}{lmtdiut_{p,i}} \ , \ p \in P, i \in I, k \in ST \tag{51}$$

$$ajhu_{p,j,k} \geq \frac{qh_{p,j} \cdot (\frac{1}{HC_j} + \frac{1}{HHU})}{lmtdjut_{p,j}} \ , \ p \in P, j \in J, k \in ST \tag{52}$$

2.2.14. First time period area and volume fixations

Equations 53 to 57 define that if a unit is installed, it needs to be installed in the first time period.

$$aijk_{p=1,i,j,k} = aijk_{p,i,j,k} \ , \ p \in P, i \in I, j \in J, k \in ST \tag{53}$$

$$aicu_{p=1,i,k} = aicu_{p,i,k} \ , \ p \in P, i \in I, k \in ST \tag{54}$$

$$aihu_{p=1,j,k} = aihu_{p,j,k} \ , \ p \in P, j \in J, k \in ST \tag{55}$$

$$vhsto_{p=1,i,k} = vhsto_{p,i,k} \ , \ p \in P, i \in I, k \in ST \tag{56}$$

$$vcsto_{p=1,j,k} = vcsto_{p,j,k} \ , \ p \in P, j \in J, k \in ST \tag{57}$$

2.2.15. Storage levels

Equations 59 and 61 restrict the storage size so that it should not exceed the maximum allowable storage size. Equations 58 and 60 define that amount of heat in each time period.

$$qhlevel_{p,i,k} = qhlevel_{p-1,i,k} + qistoI_{p,i,k} - qistoO_{p,i,k} \ , \ p \in P, i \in I, k \in ST \tag{58}$$

$$QMAX \geq qhlevel_{p,i,k} \ , \ p \in P, i \in I, k \in ST \tag{59}$$

$$qclevel_{p,j,k} = qclevel_{p-1,j,k} + qjstoI_{p,j,k} - qjstoO_{p,j,k} \ , \ p \in P, j \in J, k \in ST \tag{60}$$

$$QMAX \geq qclevel_{p,j,k} \ , \ p \in P, j \in J, k \in ST \tag{61}$$

2.3. CASE related equations

In this subsection case related equations are presented. The case study in this work is an oxyfuel power production process that captures CO_2. The equations in this subsection are partly dependent on regressions made with the simulation model.

Equation 62 gives the amount of electricity produced in a steam turbine as function of heat capacity flowrate of condensed feed water. Equation 7 gives the amount of feed water as a function of district heat consumption. Equation 64 gives the relation between condensed feed water an flue gas. Equation 65 gives the amount of electricity consumed in the compressors of the CO_2 separation unit as a function of gas flow. Equation 66 gives the amount of electricity consumed in the compressors as a function of gas flow in the Air Separation Unit. Equation 67 shows that the heat capacity flowrate entering the second compressor in the Air Separation Unit equals the exiting flow in the first compressor. Similarly equation 68 show this relation between the third and second compressor. Equation 69 gives the relation between oxygen flow into boiler and flue gas exiting the boiler. Equation 70 splits the heat capacity flowrate of flue gas into recirculated flue gas going back to the boiler and into a CO_2 flow entering the CO_2 Separation Unit. Equation 71 gives the heat capacity flowrate relation of recirculated flue gas and flue gas. Equations 72 to 74 define the heat capacity flowrate relations of streams entering subsequent compressors in the CO_2 Separation Unit. Equation 75 provides an relation between produced district heating and the market electricity price.

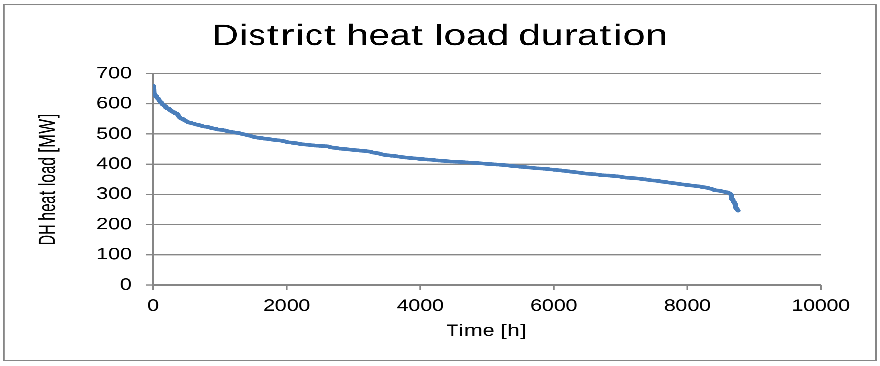

Figure 3: Annual district heating duration curve

$$wTurb_p = 931 \cdot fcI_{p,j=2} \ , \ p \in P, j \in J, \tag{62}$$

$$fcI_{p,j=2} = \frac{QDD(p) \cdot 1000}{2013.0895} \ , \ p \in P, j \in J, k \in ST \tag{63}$$

$$fhI_{p,i=4} = 2.1225 \cdot fcI_{p,j=2} \ , \ p \in P, i \in I, j \in J, k \in ST \tag{64}$$

$$wCO2_p = 111.499 \cdot fhI_{p,i=6} + 108.929 \cdot fhI_{p,i=7} + 101.807 \cdot fhI_{p,i=8} \ , \ p \in P, i \in J, \tag{65}$$

$$wAsu_p = 5479.6 \cdot fhI_{p,i=1} + 5479.6 \cdot fhI_{p,i=2} + 4445 \cdot fhI_{p,i=3} \ , \ p \in P, i \in I, \tag{66}$$

$$fhI_{p,i=2} = fhO_{p,i=1} \ , \ p \in P, i \in I \tag{67}$$

$$fhI_{p,i=3} = fhO_{p,i=2} \ , \ p \in P, i \in I \tag{68}$$

$$fhO_{p,i=3} = 1.15 \cdot fhI_{p,i=4} \ , \ p \in P, i \in I \tag{69}$$

$$fhI_{p,i=4} = fhI_{p,i=5} + fcI_{p,j=1} \ , \ p \in P, i \in I, j \in J \tag{70}$$

$$fcI_{p,j=1} = 0.72 \cdot fhI_{p,i=4} \ , \ p \in P, i \in I, j \in J \tag{71}$$

$$fhO_{p,i=5} = \frac{fhI_{p,i=6}}{0.995} \ , \ p \in P, i \in I \tag{72}$$

$$fhO_{p,i=6} = \frac{fhI_{p,i=7}}{0.995} \ , \ p \in P, i \in I \tag{73}$$

$$fhO_{p,i=7} = \frac{fhI_{p,i=8}}{0.99} \ , \ p \in P, i \in I \tag{74}$$

$$pEl_p = 0.1219 \cdot QDD_p - 2.0949 \ , \ p \in P \tag{75}$$

3. Results

In this section the data and assumptions used in the oxyfuel power process case together with the obtained results are presented The case study is an oxyfuel power plant process that produces 659 MW of district heating at full load. Figure 3 shows the load duration curve of district heating. At full load, the plant produces electricity 305 MW. The Air Separation Unit (ASU) produces a gas flow of 115 kg/s from which 108 kg/s is O_2 at full load. The CO_2 Separation Unit (CSU) recovers 124 kg/s CO_2. The ASU and CSU have three compressor stages both. Table 8 provides the extracted streams from the process flowsheet used in designing the heat transfer network. In the analysis only the gas flows after the last compressor stage in ASU is allowed to be stored. Other flows could be stored as well, but here the potential for this single storage was considered to be the most interesting one. Table 7 shows the district heat loads at different time periods.

Table 9 shows the variation of the heat capacity flowrates of different streams.

Table 10 shows the main results of the synthesis model.

Period	DH load [MW]	Duration [h]
1	602.6	46/8760
2	524.1	195/8760
3	449.5	488/8760
4	373.2	621/8760
5	308.7	110/8760

Table 7: District heating loads and durations in time periods.

Stream	Description	TIN [°C]	TOUT [°C]	FCp [$\frac{kW}{°C}$]	H [$\frac{kW}{m^2 \cdot °C}$]	Storage possibility
H1	Exit from 1. compressor stage in ASU	92.9	25	756	0.03	No
H2	Exit from 2. compressor stage in ASU	125	25	756	0.030	No
H3	Exit from 3. compressor stage in ASU	106.3	25	756	0.030	Yes
H4	Flue gas from air preheater	250	90	641	0.030	No
H5	Flue gas to CSU	99	90	179	0.030	No
H6	Exit from 1. compressor stage in ASU	140	25	161.6	0.030	No
H7	Exit from 2. compressor stage in ASU	140	25	161.0	0.030	No
H8	Exit from 3. compressor stage in ASU	145.3	25	160.8	0.030	No
C1	Recycled flue gas to combustion	99	240	462	0.030	No
C2	Feed water from DH condenser	111	152	1374.3	0.30	No
HU	Hot utility (Steam)	220	220	-	5	
CU	Cold utility (Sea water)	10	10	-	1	

ACOEFF [$\frac{\$}{m^2}$] = 150
HUCOEFF [$\frac{\$}{m^2}$] = 150
CUCOEFF [$\frac{\$}{m^2}$] = 150
β [−] = 0.83
Annual Hot Utility cost [$\$/kW \cdot a$] = 80
Annual Cold Utility cost [$\$/kW \cdot a$] = 15

Table 8: Process data for oxyfuel power production case.

As can be seen from the results, an annual investment potential of 3.4 M$ for storing the gas flow (stream H3) after the last compression stage in ASU can be seen. Table 11 shows which streams exchange heat between each other in the case when storage is allowed. Most of the heat exchange occurs between the flue gas (H4) and the feed water (C2). Some heat is exchanged between the streams in CO_2 capture process (Streams H5 and H6) and feed water (C2), but no heat of streams in ASU (H1, H2 and H3) are used.

4. Conclusions

Heat exchanger network synthesis has been an active research topic for decades. This is mainly due to the fact that in industrial processes there is a lot of potential heat that can recovered and with efficient heat exchanger networks this heat can be recovered cost-efficiently. Most of the previous work has been concentrated in synthesizing networks where streams having constant properties (heat capacity flowrates, start and end temperatures) are integrated between each other. In some situations these properties vary so much that flexibility of the networks become an important design objective. One option for increasing the

Stream	Nominal inflow FCp [$\frac{kW}{°C}$]	Maximum inflow FCp [$\frac{kW}{°C}$]	Minimum inflow FCp [$\frac{kW}{°C}$]
H1	756	-500	+300
H2	756	-500	+300
H3	756	+500	+300
H4	641	-500	+300
H5	179	0	+300
H6	161.6	0	+300
H7	161.0	0	+300
H8	160.8	0	+300
C1	462	0	+500
C2	1374.3	-800	+500

Table 9: Heat capacity flowrate variations of process streams.

Case	Total cost [$\frac{M\$}{a}$]	Maximum heat stored [kW]
No storage allowed	65.1	-
Stream H can be stored	61.7	7633.7 (after period 2)

Table 10: Main results.

Period	Match	Heat exchanged [kW]
Period 1	H4, C2	51148
Period 1	H6, C2	182
Period 1	H7, C2	157
Period 2	H4, C2	44781
Period 3	H4, C2	38409
Period 4	H4, C2	31891
Period 5	H4, C2	26376

Table 11: Match results when storage allowed.

flexibility of heat exchanger networks is to store the heat of streams in some time period and use this stored heat in some other time period.

In this work a model for synthesizing flexible heat exchanger networks is presented. The model incorporates also the possibility of including heat storage. The model is based on the simultaneous stage-wise superstructure called Synheat, but due to the existence of heat storage and unit by-passes, the energy balances after each stage are nonlinear functions. This naturally increases the complexity of solving the model, but on the other hand no isothermal mixing assumption is necessary. Thus there is a possibility to find better networks, but the importance of finding good initial values becomes more important especially if algorithms that are not able to guarantee global optimal solutions are used to solve the problem.

The developed model is tested in a case study that is an oxyfuel power plant producing both heat for a district network and electricity while capturing CO_2 from the flue gases. The district heating load varies in different time periods. In the case study only one stream is allowed to be stored. The results applying the model show that an annual investment potential of 3.4 M$ is possible if only a single stream is allowed to be stored temporarily. Thus heat storage can provide a cost-efficient solution for increasing the flexibility of heat exchanger networks operating in varying conditions.

Aaltola, J., 2002. Simultaneous synthesis of flexible heat exchanger network. Applied Thermal Engineering 22 (8), 907–918.
Floudas, C., Grossmann, I., 1986. Synthesis of flexible heat exchanger networks for multiperiod operation. Computers & Chemical Engineering 10 (2), 153–168.
Floudas, C., Grossmann, I., 1987. Synthesis of flexible heat exchanger networks with uncertain flowrates and temperatures. Computers & Chemical Engineering 11 (4), 319–336.
Konukman, A., Çamurdan, M., Akman, U., 2002. Simultaneous flexibility targeting and synthesis of minimum-utility heat-exchanger networks with superstructure-based MILP formulation. Chemical Engineering and Processing 41 (6), 501–518.
Tantimuratha, L., Asteris, G., Antonopoulos, D., Kokossis, A., 2001. A conceptual programming approach for the design of flexible HENs. Computers & Chemical Engineering 25 (4-6), 887–892.
Verheyen, W., Zhang, N., 2006. Design of flexible heat exchanger network for multi-period operation. Chemical Engineering Science 61 (23), 7730–7753.
Yee, T. F., Grossmann, I. E., 1990. Simultaneous optimization of models for heat integration – II. Heat exchanger network synthesis. Computers and Chemical Engineering 14 (10), 1165–1184.