Exergy and Structural Analysis of an Absorption Cooling Cycle and the Effect of Efficiency Parameters

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Abstract

Absorption cycles are an alternative to compression cycles in cooling and refrigeration applications. Our analysis of an absorption cycle is based on the exergy and the structural analysis. Once the exergy analysis has been achieved, the coefficients of structural bonds (CSBs) of the main heat and mass exchangers can be determined by a structural analysis. The CSBs show how the modification of the irreversibility of one component, by means of a variation of its efficiency, affects the whole cycle. It will be wise to put much of the design effort in improving the efficiency of a component, knowing that a slight decrease of the irreversibility of that component, thanks to a higher efficiency, results in an important improvement in the total irreversibility of the cycle. This methodology is applied to a single effect ammonia-water absorption cooling cycle. We also study how the selection of efficiency parameters affects the results comparing CSBs of heat exchangers obtained from the minimum temperature differences or the UA-values.

Results show that the UA is a more suitable parameter than the minimum temperature difference. Concerning the CSB values, we obtain very high values for the refrigerant heat exchanger. Values above one are also observed for the absorber, condenser and generator.

Lower values are found for the generator and the solution heat exchanger. A more detailed analysis should investigate the dependence of the CSB values on the range of efficiencies. As a further step, these results could be used in the thermoeconomic analysis and economical optimization.

Keywords: Absorption cycle, ammonia-water, single effect, exergy analysis, structural analysis, coefficients of structural bonds

1. Introduction

Cycles used for cooling and refrigeration are mostly based on mechanically driven vapor compression cycles. As the cooling demand in summer in countries with a hot climate leads to a peak in electricity consumption, the use of alternative technologies should be favored.

One possibility consists in absorption cycles (Herold et al., 1996; Ziegler, 2002). Their principal advantages compared to mechanically driven compression cycles are that they use natural refrigerants and, consequently, neither do they contribute to the destruction of the ozone layer nor to the global warming effect, and that they are thermally driven and consume only a little electrical energy. Besides, some circulating pumps do not have moving parts. Absorption cycles use a working pair consisting of a refrigerant and an absorbent. Generally these are water-lithiumbromide (LiBr) or ammonia-water. The basic absorption cycle structure is the single effect, with four basic components: absorber, generator, evaporator and condenser.

Nowadays one important drawback is the comparatively higher initial cost of absorption cycles compared to compression cycles. In order to reduce the cost of the absorption cycles, we try to apply the thermoeconomic analysis and optimization to get more cost-effective designs (Kotas, 1995; Bejan et al., 1996), This has been done to some extent for compression systems,(Wall, 1991; Dentice d'Accadia and de Rossi, 1998; Dingeç and Ileri, 1999; Ferrer et al., 2001; Dentice d'Accadia and Vanoli, 2004; Zhang et al., 2004), but less for absorption systems. (Tozer and Lozano, 1999; Sahin and Kodal, 2002; Misra et al., 2003; Boer et al., 2004).

In this work we will present how we use the structural method of thermoeconomic optimization. The exergy analysis can simplify this optimization by structural coefficients (Beyer, 1970; Beyer, 1974). They show how local irreversibilities in components affect the overall irreversibility rate of the cycle.

In our case we will use the coefficients of structural bonds (CSB). The CSB of a component k, which is obtained by a parameter x_i, is defined by

$$CSB_{k;i} = \left(\frac{\partial \dot{I}_t}{\partial \dot{I}_k} \right)_{xi=var} \qquad (1)$$

I_k is the irreversibility rate of the component k, I_t is the irreversibility rate, also called the exergy loss, of the whole cycle. In order to obtain the CSB we study the effect of a variation of a parameter x_i, which can be an efficiency-related parameter, on the irreversibility rate in the component under consideration and on the whole cycle. Structural coefficients consider how the irreversibility of the whole cycle changes when we modify the irreversibility of one component by means of a variation of its efficiency. If a slight decrease of the irreversibility of one component due to a higher efficiency causes an important improvement in the total irreversibility of the cycle, it will be wise to put much of the design effort into improving the efficiency of this component. In the case of a high coefficient of structural bonds, the benefit of a more efficient and thus more expensive component on the performance of the whole cycle will be considerable. Otherwise, if the coefficient of structural bonds is low, near or lower than unity, an improvement of the efficiency of the considered component is not economically worthwhile.

Modeling starts with the first law of thermodynamics' analysis (Fernandez-Seara and Vazquez, 2001; Chua et al., 2002; Laouir et al., 2002; Fernandez-Seara et al., 2003). Once having obtained the corresponding results we can achieve the exergy analysis in order to determine the irreversibilities (Ataer, 1990; Ataer and Gögus, 1991; Karakas et al., 1990; Best et al., 1993). Afterwards, we can achieve the structural analysis using the coefficients of structural bonds.

In our study this methodology will be applied to an ammonia-water single effect cycle.

2. Description of the Absorption Cycle

Figure 1 shows a single-effect ammonia-water absorption cycle. Basic components are the absorber (A), the condenser (C), the generator (G), and the evaporator (E). The cycle is completed by the refrigerant heat exchanger (RHE), the solution heat exchanger (HE), the condenser of the rectification column, also called dephlegmator (D), and the adiabatic rectification plates. There are three adiabatic plates, which is the optimum number for this configuration (Laouir et al., 2002).

The figure presents the cycle in a pressure-temperature plot. The pressure increases upwards and temperatures increase to the right. In the following description, letters refer to the components, numbers to the state points.

The solution circulates between the absorber (A), where the refrigerant is absorbed at low pressure, and the generator (G), where the refrigerant is desorbed at high pressure (state points 1 to *6*). The strong solution leaves the absorber (A), is preheated in the solution heat exchanger (HE), and enters the rectification column in central plate two. Temperature and water concentration increases from plate one to plate three.

The generator acts as the reboiler of the rectification column. The weak solution (4) leaves towards the absorber. In the dephlegmator, we obtain the necessary liquid reflux, while the rest of the vapor (9) condenses completely in the condenser (10) and is cooled in the refrigerant heat exchanger (RHE). The condensate expands in the refrigerant throttle valve and enters the evaporator (E). Due to the water content of the mixture, the evaporation takes place with a temperature glide. The temperature increases during the vaporization process as the liquid contains less and less ammonia, which is the more volatile component. Vaporization in the evaporator is only partial. For total evaporation, the temperature glide would be too high. The cycle is closed when the vapor with a small liquid fraction (14) passes through the refrigerant heat exchanger (RHE) and enters the absorber (A). Streams 15 to 24 are the external heat transfer fluids (in all cases we assume this is water), which deliver or extract heat.
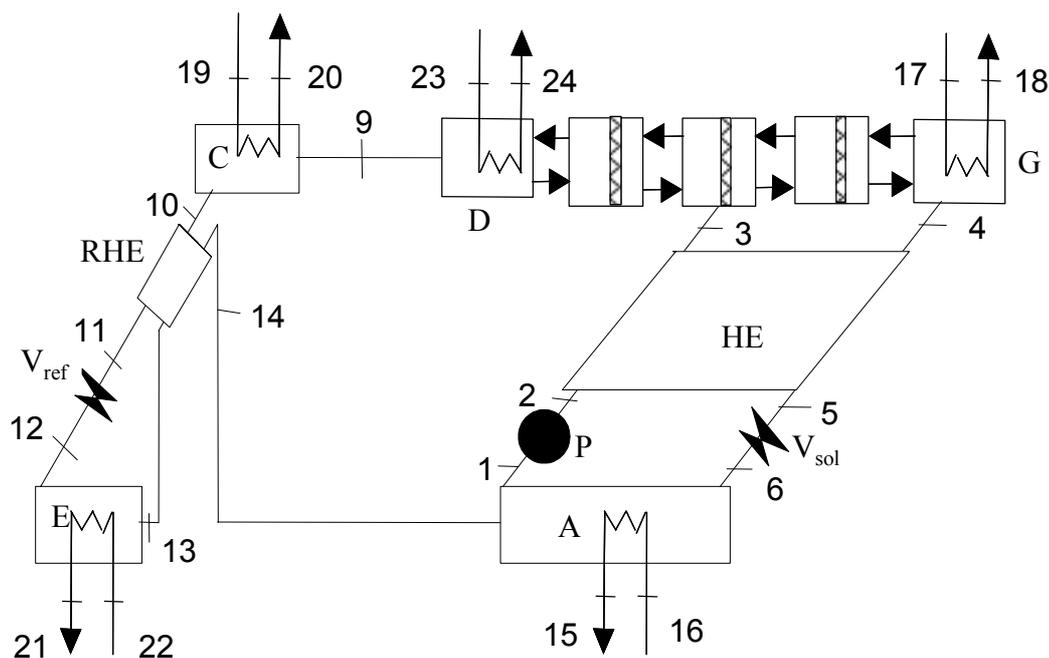
Figure1. Single effect ammonia-water absorption cycle.

The useful production of cooling takes place in the evaporator, heat is supplied in form of hot water to the generator, and heat is dissipated at an intermediate temperature in the condenser and the absorber.

To obtain the necessary pressure changes, the cycle includes a solution pump (P), a refrigerant expansion valve (V_{ref}) and a solution expansion valve (V_{sol}).

2.1 Methodology of simulation for absorption cycle

A thermodynamic model was developed for the absorption cycle using the program Engineering Equation Solver (EES). Properties for ammonia water are given by Tillner, Roth and Friend (1998).

We evaluated properties for all state points, including specific exergies. After conducting the exergy analysis, we computed the irreversibilities.

The input data, output data, main assumptions and operating conditions are presented below.

The input data are:

1- The cooling power of the evaporator, which is fixed in all calculations
2- The inlet and outlet temperatures of the external fluids
3- The minimum temperature difference in the heat and mass exchangers

The output data are:
1- The pressures, temperatures, concentrations, mass flows, enthalpies, entropies and exergies of each current
2- The thermal or, in the case of the solution pump, mechanical power and irreversibility rate of the main components
3- The COP and exergetic efficiency

The main assumptions are:
1- It is a steady cycle
2- There are no heat losses
3- There are no pressure losses
4- The refrigerant leaving the condenser is saturated liquid
5- The mass exchange efficiencies in absorber and generator are 0.9
6- On adiabatic rectification, plates leaving liquid and vapor are in equilibrium
7- The solution and refrigerant valves are adiabatic

The operating conditions are:
1- Evaporator cooling capacity 1000 kW
Temperatures:
1- Chilled water inlet/outlet 6/12ºC
2- Cooling water (parallel flow through absorber, condenser and dephlegmator inlet/outlet)27/32ºC
3- Hot water inlet 90ºC
4- Minimum temperature difference in the heat exchangers 5 K

The hot water outlet temperature is adjusted to minimize the heat capacity rate mismatch in the generator.

Steady state mass, energy and exergy balances for the components of the cycles are established as follows:

Global mass balance:

$$\Sigma \dot{m}_i = \Sigma \dot{m}_e \qquad (2)$$

Mass balance for ammonia:

$$\Sigma \dot{m}_i z_i = \Sigma \dot{m}_e z_e \qquad (3)$$

Energy balance:

$$0 = \dot{Q} - \dot{W} + \sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e \qquad (4)$$

Exergy balance:

$$0 = \sum_i (1 - \frac{T_0}{T_i}) \dot{Q}_i - \dot{W} + \sum_i \dot{m}_i e_i - \sum_e \dot{m}_e e_e - \dot{I} \qquad (5)$$

Specific exergy (equation (6)) is made up of a physical (equation (7)) and a chemical component (equation (8)).

$$e = e_{ph} + e_{ch} \qquad (6)$$

$$e_{ph} = h - h_0 - T_0(s - s_0) \qquad (7)$$

$$e_{ch} = \sum_i x_i e_{ch,i} + RT_0 \sum_i x_i \ln(\gamma_i x_i) \qquad (8)$$

The properties indicated with the subscript 0 refer to the environmental state, which is defined as 25ºC and 1 bar.

3. Results and Discussion

3.1 Energetic analysis

Results of the energetic analysis for the different state points are presented in TABLE I.

These results, as well as the results for exergy analysis, are obtained by fixing a minimum temperature difference in the heat exchangers of 5 K, with the exception of the dephlegmator, which has a minimum temperature difference of 15 K.

3.2 Exergy analysis

The next step was the exergy analysis. After determining the exergies of the state points, we conducted the exergy analysis. Irreversibilities for the main components are shown in TABLE II.

The highest irreversibilities are found in the absorber, followed by the evaporator, the solution heat exchanger and the generator. This already includes nearly all the main heat exchangers. The irreversibility of the condenser and the dephlegmator were lower. Smaller contributions were made by the refrigerant heat exchanger, the solution pump and the expansion valves. Irreversibilities in the adiabatic rectification plates were also low.

TABLE III presents exergy input and output to main components, including as reference also their thermal power and the design UA value.

TABLE I. RESULTS OF THE ENERGETIC ANALYSIS.

State point	T [C]	p [bar]	z [kg/kg]	m [kg/s]	h [kJ/kg]	e [kJ/kg]
1	32	4.453	0.513	8.77	72.06	27.31
2	32.6	14.29	0.513	8.77	73.27	28.7
3	74.7	14.29	0.513	8.77	273.4	46.08
4	85	14.29	0.46	7.913	299.3	57.28
5	37.6	14.29	0.46	7.913	77.43	32.64
6	37.8	4.453	0.46	7.913	77.43	31.5
9	47	14.29	0.999	0.857	1666	207.4
10	37	14.29	0.999	0.857	518.0	162.0
11	22.8	14.29	0.999	0.857	449.3	160.9
12	1	4.453	0.999	0.857	449.3	155.0
13	7	4.453	0.999	0.857	1617	53.48
14	32	4.453	0.999	0.857	1685	51.98
15	27	1	0	68.15	113.3	0.0279
16	32	1	0	68.15	134.2	0.3382
17	90	1	0	36.09	377.1	26.05
18	80.1	1	0	36.09	335.6	19.09
19	27	1	0	47.02	113.3	0.0279
20	32	1	0	47.02	134.2	0.3382
21	12	1	0	39.71	50.51	1.222
22	6	1	0	39.71	25.32	2.652
23	27	1	0	4.885	113.3	0.0279
24	32	1	0	4.885	134.2	0.3382

TABLE II. IRREVERSIBLITIES OF THE COMPONENTS OF THE ABSORPTION CYCLE.

Component	$\dot{I}$ [kW]
A	33.09
C	24.35
D	8.745
E	30.2
G	12.57
HE	42.57
P	5.581
Rectification plates	1.576
RHE	2.228
V_{ref}	5.032
V_{sol}	9.035

The irreversibilities are interesting information as they indicate to us where exergy is destroyed. But their usefulness is limited in the sense that they do not show the best way to

improve the cycle. For example. it is not necessarily the best choice to increase the efficiency of the component with the highest irreversibility, in our case the absorber, as we do not know the interactions with the rest of the system.

TABLE III. ENERGY AND EXERGY FLOW OF MAIN COMPONENTS (IN KW).

Compo-nent	$\dot{Q}$ [kW]	UA [kW K^{-1}]	Exergy Input [kW]	Exergy Output [kW]	$\dot{I}$ [kW]
A	1424	264.3	54.2	21.2	33.1
C	983	79.7	38.9	14.6	24.4
E	1000	131.4	87.0	56.8	30.2
G	1499	299.8	251.2	238.7	12.6

3.3 Structural analysis

Once the irreversibilities are obtained, we can check as to how a change of the irreversibility of one component affects the rest of the cycle. This is done using the coefficients of structural bonds (Beyer, 1970; Beyer, 1974). In our case, this means that we will vary efficiency related parameters of the different heat exchangers, maintaining the values of these parameters for the other heat exchangers constant. Two different approaches are compared. In the first one we use as a parameter the minimum temperature difference ΔT_{min}, which will be varied in one component and fixed in the others. In the second case we will use the value of UA for the same purpose. Accordingly operation conditions and mass flow rates of the cycle will change, as will

be commented on in the interpretation of the results.

Figure 2 represents a plot of the irreversibility in the absorber versus the total irreversibility for different minimum temperature differences. We also include on the right scale the corresponding values of ΔT_{min}. As pressure loss is neglected with lower ΔT_{min}, the irreversibility of the absorber is reduced. But more interesting is in which way the total irreversibility is affected. This information can be obtained quantitatively by the CSB:

$$ CSB_{A;\Delta T_{min,A}} = \left(\frac{\partial \dot{I}_t}{\partial \dot{I}_A} \right)_{\Delta T_{min,A} = var} \quad (9) $$

We achieved in *Figure 2* a linear interpolation of the values of $\dot{I}_A$ versus $\dot{I}_t$. The value of 2.57 represents the slope and gives us the mean values of the CSB of the absorber. This means if the irreversibility of the absorber can be reduced by 1kW due to an efficiency increase, the total irreversibility will decrease by 2.57kW. So the benefit for the total cycle is even greater than for the component due to their interactions.

Figure 3 represents a similar plot with the difference that the parameter which is varied is UA of the absorber, and the UA-values of the other components are fixed. In order to be able to compare both figures, we plotted in the right scale also the corresponding ΔT_{min} values
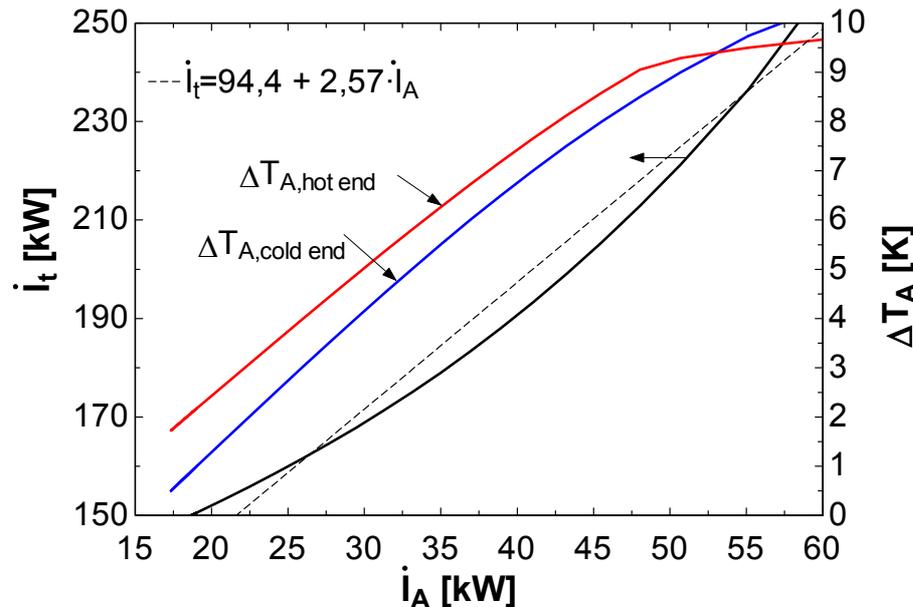

Figure 2. Irreversibility of the absorber versus total irreversibility varying ΔT_{min}.
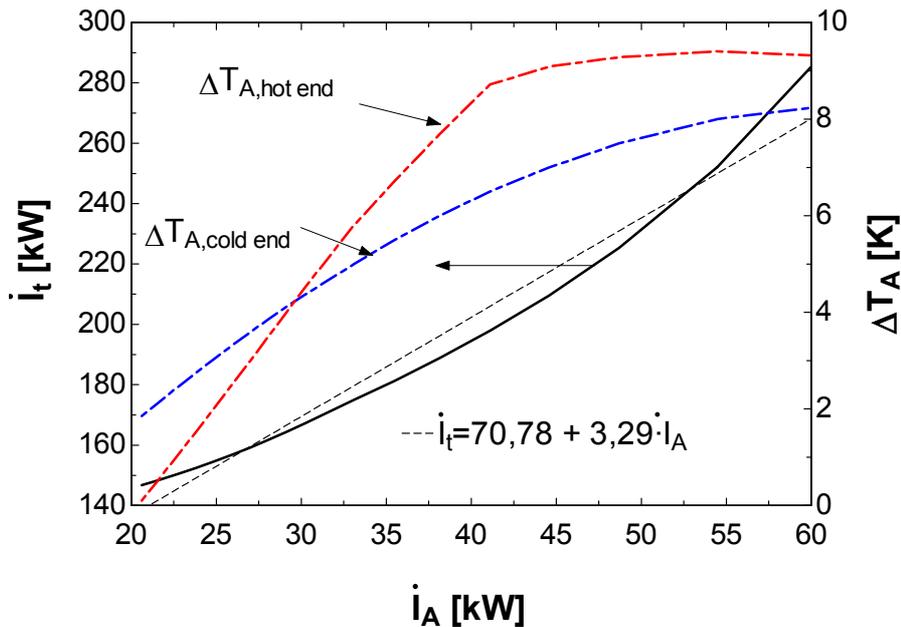
Figure 3. Irreversibility of the absorber versus total irreversibility varying UA.

The CSB is now defined by

$$CSB_{A;UA_A} = \left(\frac{\partial \dot{I}_t}{\partial \dot{I}_A} \right)_{UA_A = var} \qquad (10)$$

The value obtained by a linear interpolation is 3.29, which differs considerably from the value obtained previously. The difference lies in the behavior of the other components. In the case of fixing ΔT_{min} their efficiencies will remain similar, but their exchange area can be different. In the case of fixing UA, their size will be similar, but not their efficiencies. TABLE IV presents the results for both parameters, which in some cases differ significantly.

But which is the better parameter choice? Our purpose is the use of the CSB in the thermoeconomic optimization of the components. Thus we would like to know how the change of the design parameters of one component affects the whole cycle, while the rest of the cycle is unchanged. The term unchanged fits better parameter UA, as this means constant capital cost of the other components. So for us results obtained by variations of UA are more useful.

It is also worthwhile to observe the values. For example, it seems especially interesting to improve the refrigerant heat exchanger having a CSB of about 12. We can explain this as follows: As a design parameter we fix the cooling output. As a better refrigerant heat exchanger achieves lower enthalpies in the inlet of the evaporator, we need less refrigerant to obtain the needed cooling power. Also, proportional to the refrigerant flow, the solution flow rates will be reduced, and maintaining the UA of the heat exchangers their efficiency will increase. Maintaining the ΔT_{min} of

the components constant, their UA would decrease as the mass flows are lower. Consequently, the CSB in this case is lower with a value of about 7.

In similar ways the CSBs of the other components can be explained. These results will be discussed in more detail in a later publication.

TABLE IV. COEFFICIENTS OF STRUCTURAL BONDS CSB FOR MAIN COMPONENTS OF THE ABSORPTION CYCLE.

Component symbol	CSB obtained	
	ΔT_{min} =var.	UA =var.
A	2.57	3.29
C	2.25	2.73
E	2.78	2.50
G	1.35	2.14
HE	1.50	1.21
RHE	7.29	12.33

4. Conclusions

In our work we achieved the energy, exergy and structural analysis of an ammonia-water single effect cooling cycle. The exergy analysis helps us to determine the irreversibilities of the components of the cycle and the total cycle. As a further step we achieve the structural analysis using the coefficients of structural bonds. They indicate to us how the irreversibility change in one component affects the rest of the system. The effect of two different parameters has been tested and compared: the minimum temperature difference in the heat exchangers and their UA value. We concluded that for the purpose of a thermoeconomic optimization of the cycle, the

UA values are more appropriate, as fixing the UA value of a component its capital cost is approximately constant.

Other interesting results of our work are the values of the CSB, which in the case of some components show relatively high values. In the case of a high coefficient of structural bonds the benefit of a more efficient and thus more expensive component on the performance of the whole cycle will be considerable.

This work will be continued for other cycle configurations. Once a set of CSBs is obtained it can be used in the optimization of the components.

Acknowledgements

Nomenclature

A   absorber
C   condenser
CSB   coefficients of structural bonds
D   dephlegmator
E   evaporator
e specific exergy (kJ kg^{-1}, kJ kmol^{-1})
$\dot{E}$ exergy flow (kW)
G   generator
h   specific enthalpy (kJ kg^{-1})
HE   solution heat exchanger
$\dot{I}$ irreversibility (kW)
$\dot{m}$ mass flow
p   pressure (bar)
P   solution pump
$\dot{Q}$ heat flow (kW)
R   gas constant (kJ/kmol K)
RHE   refrigerant heat exchanger
s   specific entropy (kJ kg^{-1} K^{-1})
T   temperature (ºC or K)
UA   product of heat transfer coefficient and heat transfer area (kW/K)
V_{ref} refrigerant expansion valve
V_{sol} solution expansion valves
$\dot{W}$ mechanical power (kW)
x_i parameter in the efficiency variation of the CSB, molar concentration
z   concentration (mass fraction ammonia) (kg/kg)

Greek letters

γ activity coefficient (-)

Subscripts

0   environmental state (25ºC, 1 bar)
ch   chemical
e   exit
i   inlet, component of the mixture
k   component k
ph   physical
t   total

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