

Absorption heat transformer - state-of-the-art of industrial applications

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Abstract

The use of waste heat or low-exergy heat sources represents a strategic opportunity to reduce the environmental footprint and operation cost of industrial processes. The absorption heat transformer, also known as absorption heat pump type II, is a thermal machine which can boost the temperature of a heat flow by using a negligible amount of electrical power.

However, owing to the lack of established technical knowledge and the absence of comprehensive recordings of successful heat transformer applications, the feasibility and reliability of absorption heat transformers have been questioned and the diffusion of this technology remained limited.

Therefore, in this paper, all the industrial applications of the absorption heat transformer that are recorded in previous literature and yet unpublished reports are presented and discussed.

In addition to literature research, intense knowledge exchange with three leading manufacturers of absorption heat transformers gave an accurate perspective on the technological level of commercial products and operative installations. It is shown that between 1981 and 2019, 48 absorption heat transformers have been installed in 42 plants with a total capacity of ≈ 134 MW. Two main implementation periods, separated by 25 years of infrequent heat transformer installations, have been recognised. More than 74% of the installations were in Asia. Approximately 61% of the heat transformer installations were applied into the chemical industry.

Therefore, through the analysis of the technical challenges and their solutions, along with related economical aspects of heat transformer installations, the effective state-of-the-art of

this technology is presented and discussed.

Keywords: absorption heat transformer, absorption heat pump type II, industrial applications, heat recovery

Nomenclature

\dot{m} mass flow rate (kg/s)

\dot{Q} heat flow (W)

p pressure (Pa)

T temperature (°C)

A G C E absorber generator condenser evaporator

AH high pressure Absorber

AHT absorption heat transformer

AL low pressure Absorber

COP coefficient of performance

DDT characteristic temperature difference

EH high pressure Evaporator

EL low pressure Evaporator

HX heat exchanger

HXH high pressure heat exchanger

HXL low pressure heat exchanger

LHV Lower heating value

M motor valve driver

PID proportional integral derivative controller

ROI return of investment

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RP refrigerant pump
RPH high pressure refrigerant pump
RPL low pressure refrigerant pump
SP solution pump
SPL low pressure solution pump
SV solution valve
SVH high pressure solution valve
SVL low pressure solution valve
VSD variable speed driver

Subscripts

0 1 2 pressure level
0 1 2 temperature level
A G C E absorber generator condenser evaporator
in inlet
out outlet
p poor solution
R refrigerant
r rich solution
set set value

1. Introduction to absorption heat transformer technology

Recent environmental, legislative, and energy provision considerations have shifted the priority-relationship between the initial investment and the running cost of thermal systems. In order to effectively use discarded or unutilised thermal energy sources with a low exergetic level, vapour absorption is a key technology that reduces the primary energy consumption and the environmental impact. In this respect, absorption heat transformers (absorption heat pumps type II) play a strategical role in the recovery of waste heat and thermal energy from sources with a low exergetic level; this is due to their ability to utilise heat at a certain temperature level and release approximately half of this heat at a higher temperature level with a negligible amount of mechanical work input.

The absorption heat transformer process works in reverse to the absorption heat pump process. The process is driven by a heat flow \dot{Q}_1 at an intermediate temperature level T_1 , which splits into heat flow \dot{Q}_2 at a high temperature level T_2 (upgraded) and heat flow \dot{Q}_0 at a low temperature level T_0 (downgraded) (see figure 1). The left-hand side of the figure 2 shows the main components of a single-effect heat transformer: absorber, generator, condenser, evaporator, solution heat exchanger, solution valve, refrigerant pump and solution pump. It also shows the relation of temperature and pressure levels between the main components. The temperature levels T_0, T_1, T_2 can be roughly interpreted as the mean values of the inlet and outlet temperatures $T_{0,in/out}, T_{1,in/out}, T_{2,in/out}$ at the corresponding main heat exchangers.

At the generator, the refrigerant is desorbed out of the solution by the driving heat. The solution with a lower mass fraction of the refrigerant is pumped by the solution pump into the absorber at a higher pressure level through a solution heat exchanger for internal heat recovery. At the absorber, the solution absorbs the refrigerant vapour which was evaporated at the evaporator by the driving heat. The heat of absorption is released as upgraded heat. The solution rich in refrigerant flows through the solution heat exchanger and valve to the generator at a low pressure level. At the condenser, the refrigerant vapour coming from the generator is condensed. The condensation heat is rejected to a heat sink at the low temperature level T_0 , usually the ambient temperature. The liquid refrigerant is then pumped to the evaporator at a high pressure level.

On the right-hand side of figure 2 a double-lift cycle in *serial flow* design is depicted [1]. Here, an absorber and an evaporator at a higher pressure level are added to further increase the temperature of the upgraded heat flow \dot{Q}_2 . In this cycle the low pressure absorber AL drives the higher pressure evaporator EH by internal heat exchange. The higher temperature boost is compromised by the lower heat flow \dot{Q}_2 .

The coefficient of performance (COP) is defined as the ratio of the upgraded heat flow \dot{Q}_2 to the driving heat flow \dot{Q}_1 . The driving heat flow \dot{Q}_1 equals the sum of the heat flow put into evaporator \dot{Q}_E and generator \dot{Q}_G . The upgraded heat flow \dot{Q}_2 corresponds to the heat flow released from the absorber \dot{Q}_A and the rejected heat flow \dot{Q}_0 to the heat flow leaving the condenser \dot{Q}_C .

Accordingly, the expected COP of single-effect and double-lift heat transformers approaches 0.5 [2, 3] and 0.3 [4, 5], respectively, even at part-load operation [6, 7]. These numbers seem to be low, but this is because low-grade energy as the driving heat is used. As presented by [8], the second law efficiency of single-effect heat transformer cycles working with H₂O/LiBr is commonly between 70 % to 80 %, and for a double-lift approximately 70 %.

$$COP = \frac{\dot{Q}_2}{\dot{Q}_1} = \frac{\dot{Q}_A}{\dot{Q}_G + \dot{Q}_E} \quad (1)$$

In general, the output capacity of a heat transformer depends on the working conditions, and specifically on the relation between the temperature thrust and the temperature lift. The temperature thrust is defined as the difference between the intermediate temperature level T_1 and the low temperature level T_0 , whereas the temperature lift is defined as the

difference between the high temperature level T_2 and intermediate temperature level T_1 . Generally, for a given design of a heat transformer (e.g., fixed heat transfer areas), the capacity decreases when the high temperature level T_2 increases. On the other hand, the capacity increases when the low temperature level T_0 decreases or when the intermediate temperature level T_1 increases. [9, 6, 7, 10]

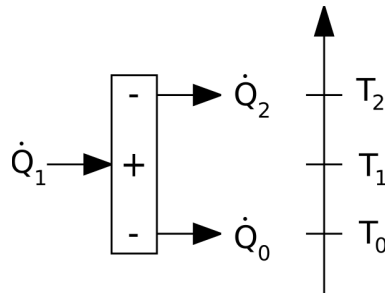


Figure 1: Blackbox scheme of the absorption heat transformer process

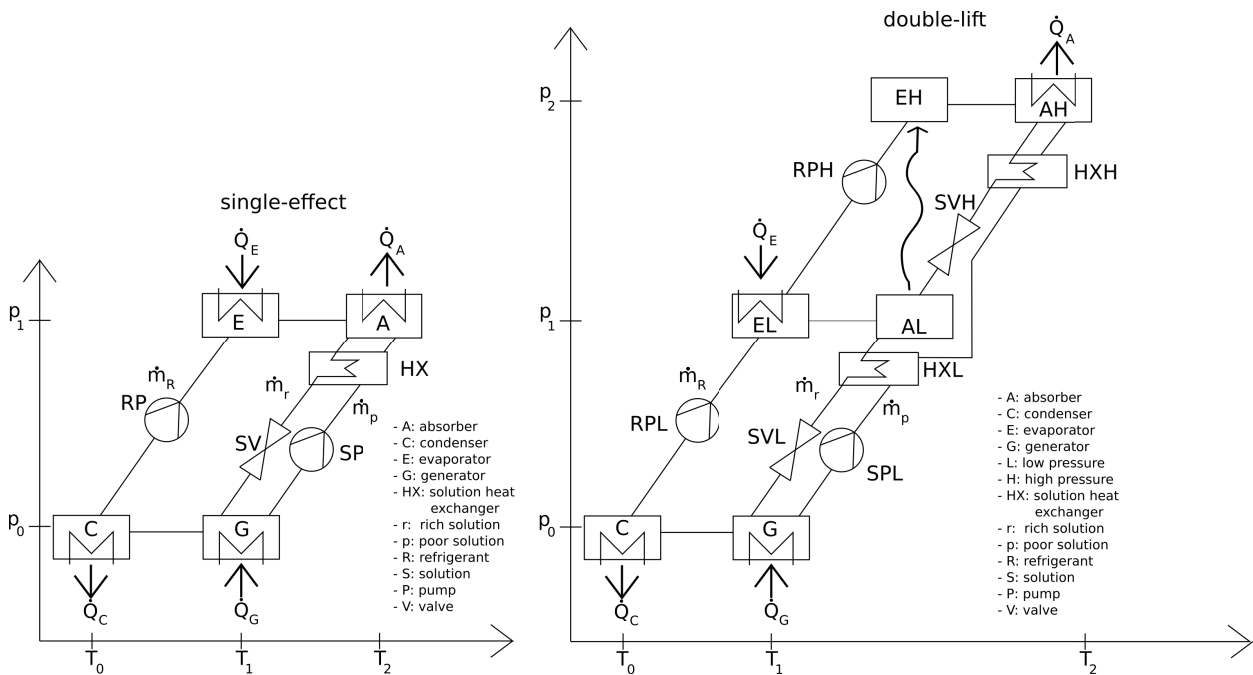


Figure 2: Scheme of the absorption heat transformer process (left: single-effect; right: double-lift (serial flow))

Following the introduction of absorption devices, in general, a section about absorption heat transformers is included in the textbooks [11, 133-142], [12] and [13] (Japanese textbook).

This study originates from the observation that there are relatively few operative applications and manufacturers of commercial products for heat transformers. Heat transformer technology has experienced a relatively long and slow-paced development.

Europe for instance, has implemented the heat transformer technology in a few cases in the 1980s followed by no new system commercialization or operative plants until 2014, except for the installations in Netherlands (1991), Sweden (1995) and Germany (1998).

These installations worked only for a few years because of corrosion problems. Owing to the technical issues related to conventional working fluids (such as corrosion at high temperature, crystallisation and purge of non-condensable gases), as well as the lack of conclusive reports about these issues and possible technical solutions, the feasibility and reliability of absorption heat transformers have been questioned [14]. Although limited in number, successfully operating installations have identified the absence of comprehensive reports on the state of art of this technology as the cause for loss of established knowledge, which has hindered its development and spreading. To the best knowledge of the authors, comprehensive information about the technical details of successful heat transformers installed in industrial applications and complete collections of industrial implementations are not available in existing literature. This has limited the confidence on this technological possibility and potentiality on the end-user side. For these reasons, a comprehensive report of industrial installations, along with the main technical challenges and possible solutions, is considered as a valuable source that contributes to filling the knowledge gap needed for the effective diffusion of this technology.

This paper does not focus on discussing different cycle configurations featuring multi-staging or different workings pairs, because other literature references have comprehensively covered these themes, e.g. [4], [15] and [16]. The applicative and thermo-economical analysis of all the industrial applications, along with the main technical challenges and possible solutions are rather taken as the representative knowledge of the effective state-of-the-art of this technology.

2. Methodology

Information about the technical details of heat transformers installed in industrial applications and complete collections of industrial implementations are not available in existing literature. Previous review papers about absorption heat transformers [17, 18] and about absorption heat pumps [19] include only a few examples. These papers attempt to present an overview of the research outputs related to absorption heat transformers and do not comprehensively report on industrial installations along with the related technical issues and solutions. Accordingly, to fill the gap in the technical knowledge of absorption heat transformers, the main objective of this study is to clarify the technical feasibility and reliability of this technology, as well as its implementation field. A comprehensive report of industrial installations, along with some technical considerations, is considered as a valuable source that contributes to this technology.

The literature review covers international and domestic publications, research and technical reports, and commercial catalogues. The board of authors was able to review literature in different languages, especially in English, Japanese and German. Consequently, the information gathered from the literature review was expanded with references to unpublished information, internal reports and data by the authors, particularly by the authors employed

in leading manufacturers of absorption heat transformers. Additionally, a workshop with the leading manufacturers and mutual exchanges between the academic institutions involved were organized.

The inclusion of information from the manufacturers resulted to be of primary importance, given that since 1995 [20] detailed information about only four heat transformer (heat transformer No. 22, 25, 26, 27) has been published in open literature. Furthermore, no discussion about technical issues (e.g. corrosion, crystallization) and their technical solutions have been reported.

The collected information about absorption heat transformer installations is combined in table 1, 2, 3 and 4, and discussed. The operative benefits and feasibility (environmental and economical) are reviewed in section 5, along with several examples demonstrating the viability and profitability notwithstanding the higher initial investment cost when compared to conventional technologies. Finally, by referring to related patents and technical assessments, the main technical challenges and possible solutions are discussed in sections 6 to 11.

3. Overview of installed heat transformers

Tables 1 and 2 include all the heat transformers in industrial applications which can be found in the literature, enhanced by unpublished information given by the authors of this paper (marked as *authors*). In these tables, starting from 1981, a total of 43 heat transformer applications, with a total capacity of ≈ 134 MW, are recorded. In figure 3 the installed heating capacity (upgraded heat flow) of the installations per year is plotted for each year. The heating capacity is plotted in logarithmic scale, to make the installations with small capacities visible. Four installations are not included in this figure because their date of installation or their capacity is unknown (No. 16, 19, 23, 24).

Along with the capacities, the temperature lift and the continent of the installations are also visualized in the figure. The temperature lift is defined in table 1 as the difference between the input temperature of the driving heat at the intermediate temperature level $T_{1,in}$ and the output temperature of the revaluated heat at the high temperature level $T_{2,out}$ (see table 1).

There are two active periods of heat transformer installations in the last 38 years. Between the year 1981 and 1987, 18 heat transformers with capacities ranging from 350 kW to 6.78 MW and a total heating capacity of ≈ 35 MW were installed. The second period is considered to be from 2013 to 2019. In this second period, 16 installations with capacities ranging from 450 kW to 42.17 MW and a total heating capacity of ≈ 67 MW were commissioned. In the year 2019, two heat transformers are installed. The biggest application consists of six devices.

All heat transformers of the second period and a heat transformer from the year 2008, which has been working for the past 11 years, are still running. A heat transformer applied in a distillation plant had achieved the longest working period of 29 years (1984 to 2013) until it was replaced (see No. 7 and No 28 in table 2). The currently running installations

are mostly placed in China (12 installations), and the rest are placed in Japan (2 installations), USA, Italy and Germany.

In the 25 years between these two periods, only nine devices (included installations No. 23, 24 and 19) with a total capacity of ≈ 32 MW were installed.

For 40 out of 43 installations (total capacity ≈ 129 MW), the working pair $\text{H}_2\text{O}/\text{LiBr}$ was used. Only two installations (≈ 2 MW) operate with $\text{H}_2\text{O}/\text{NaHO}$ as working pair. Since 1998, only the working pair $\text{H}_2\text{O}/\text{LiBr}$ is used. Accordingly, this working pair can be considered as state-of-the-art for the absorption heat transformer technology.

The inlet temperatures of driving heat source $T_{1,in}$, and of the rejected heat $T_{0,in}$, and the outlet temperature of the upgraded heat $T_{2,out}$ are taken as the the temperature levels to discuss the operative range of these installations. 32 heat transformer installations feature inlet temperatures of the rejected heat between 20°C and 35°C ; for three installations $T_{0,in}$ is lower than 20°C , and for one installation higher than 35°C . The maximum among the recorded inlet temperature of the rejected heat is 46°C , while the minimum is $\approx 11^\circ\text{C}$. No information about this temperature is available for the remaining seven installations.

37 heat transformer installations among the 43 listed in table 1 operate with an inlet temperature of the driving heat $T_{1,in}$ between 75°C and 110°C ; two installations show lower inlet temperatures of the driving heat (the minimal value being 56°C); four heat transformer installations operate with higher values of $T_{1,in}$ (the maximum value being 130°C).

The highest and the lowest outlet temperature of the upgraded heat recorded among the heat transformer installations are 165°C and 80°C , respectively. 33 heat transformer installations achieve an outlet temperature of the upgraded heat between 110°C and 145°C , while six installations operate above this range and four below.

Furthermore, the temperature lift the applications are designed for are quite diversely distributed over the range of 5 K and 60 K. This demonstrates the flexibility of the heat transformer technology. Depending on the required temperature lift and the given cooling temperature (T_0), single-effect or double-lift cycles are chosen to be implemented. In most of the cases (34 out of 43), single-effect cycle can meet the temperature requirements. In four cases, double-lift heat transformers are needed.

As shown in the list of installations, the mean value for the coefficient of performance is $COP \approx 0.47$ for single-effect heat transformers; therefore, it can be taken as a reference value for estimations in the implementation of a heat transformers. For double-lift heat transformers operated in laboratories, a mean value of $COP \approx 0.3$ is recorded in [1, 21, 22].

In table 2, the manufacturers of the heat transformers are also listed. Some manufacturers, such as Kawasaki Heavy Industries, Tokyo Sanyo Electric Co. Ltd. and GEA, have stopped offering absorption heat transformers. The following manufacturers are presently offering absorption heat transformers as a part of their catalogues.

- Ebara Refrigeration Equipment & Systems Co., Ltd. [23]
- Johnson Controls-Hitachi Air Conditioning (Japan) [24]
- Jiangsu Shuangliang Eco-Energy Co., Ltd. (China) [25]

- Thermax Ltd. - Absorption Cooling [26]

In addition to the industrial installations, there are/were a few laboratory installations in Japan [1], Germany [21, 27, 28, 6, 29], Mexico [30, 31], Sweden [32], India [33, 34], Italy [35] and U.K. [36] .

Table 1: Technical information of installations, Working pair: H₂O/LiBr, except No. 21, 4 (NaHO) and 19 (N/A), * marks assumptions based on given information, E: Evaporator, G: Generator

No.	capacity [MW]	working conditions						cycle	COP	references
		$T_{0,in}$ [°C]	$T_{0,out}$ [°C]	$T_{1,in}$ [°C]	$T_{1,out}$ [°C]	$T_{2,in}$ [°C]	$T_{2,out}$ [°C]			
43	1.83	32	N/A	100	N/A	N/A	148	Double	N/A	authors
42	0.55	20	N/A	130	N/A	N/A	148	Single	N/A	authors
41	0.64	32	N/A	100	N/A	N/A	130	Single	N/A	authors
40	0.89	23	29	96.1	80	139	144.5	Single	0.47	authors
39	4.68	32	N/A	56	N/A	N/A	80	Double	N/A	authors
38	0.77	32	N/A	56	N/A	N/A	90	Double	N/A	authors
37	1.04	32	N/A	115	N/A	N/A	120	Single	N/A	authors
36	0.67	32	N/A	91	N/A	N/A	165	Double	N/A	authors
35	1.8	32	N/A	97	N/A	N/A	130	Single	N/A	authors
34	42.17	32	N/A	120	N/A	N/A	158	Single	N/A	authors
33	1.2	N/A	N/A	93	75	125	135	Single	0.46	[8] authors
32	2.61	28	N/A	105	100	N/A	144	Single	N/A	authors
31	4.19	28	38.5	108	100	152	157	Single	0.47	[8] authors
30	0.45	N/A	N/A	90	80	95	105	Single	0.47	[8] authors
29	1.83	30	N/A	97	N/A	N/A	125	Single	N/A	authors
28	1.65	15	N/A	81	81	120	125	Single	0.46	[37] authors
27	2.48	25	30	78	78	107	112	Single	0.45	[38] authors
26	0.15	27	32	90	85	133	137	Single	0.48	[38, 39] authors
25	5	28	30	98	N/A	N/A	110	Single *	0.47	[40, 41]
24	7	28	30	98	N/A	N/A	110	Single *	0.47	[41, 8]
23	7	28	30	98	N/A	N/A	110	Single *	0.47	[41, 8]
22	4	N/A	N/A	80	N/A	N/A	140	Double	N/A	[42]
21	0.08	46	46	98(G) 105(E)	98(G) 105(E)	115	120	Single	N/A	[32]
20	4.1	20	26	90	85	110	130	Single	0.46	[14]
19	2	N/A	N/A	97	94.5	N/A	133	N/A	N/A	[20]
18	3.37	26.7	30.6	78.7	78.7	N/A	111.5	Single	0.48	[43]
17	1.2	N/A	N/A	78	N/A	N/A	108	N/A	N/A	[44, 45]
16	N/A	22.3	N/A	88	N/A	N/A	122	N/A	N/A	[44, 45]

15	1.38	22	31.4	100	100	100	136	Single	0.44	[20, 46]
14	1.1	N/A	N/A	100	100	N/A	144	Single *	0.44	[20, 47]
13	1.09	27	30	125	91	134	139	Single *	0.49	[20, 48]
12	2.71	32	37	95	95	25	131	Single *	0.47	[20, 48]
11	1.88	31	37	100	100	90	143	Single	0.48	[44, 45]
10	0.35	32	37	95	85	95	120	Single *	0.49	[20, 48]
9	6.78	10.7	36.6	103.3	103.3	130.8	144.9	Single	0.49	[20, 48, 47, 49]
8	3.3	31	37	100	100	90	143	Single *	0.48	[20, 48]
7	1.67	15	20	80	80	111	116	Single *	0.48	[20, 48]
6	0.93	20	30	80	80	119	124	Single *	0.48	[20, 48, 50]
5	1	N/A	N/A	100	100	N/A	145	N/A	N/A	[20]
4	2.35	31	N/A	98	88	127	132	Single *	0.48	[20, 48]
3	1.88	32	36	80.5	80.5	100	112	Single *	0.48	[20, 48]
2	1.66	28	32	83	83	100	111	Single	0.48	[20, 48, 51, 9]
1	2.35	26	32	98	88	127	133	Single	0.47	[20, 48, 50]

Table 2: Operation information of installations, * marks assumptions

No.	country	operator	operation period		manufacturer
			start [year]	end [year]	
43	China	N/A	2019	running	Ebara
42	China	N/A	2019	running	Ebara
41	China	N/A	2018	running	Ebara
40	USA	UNILEVER	2018	running	Thermax Ltd.
39	China	N/A	2016	running	Ebara
38	China	N/A	2016	running	Ebara
37	China	N/A	2016	running	Ebara
36	China	N/A	2016	running	Ebara
35	China	N/A	2016	running	Ebara
34	China	N/A	2015	running	Ebara
33	Italy	Baronia Pasta	2015	running	Thermax Ltd.
32	China	N/A	2014	running	Ebara
31	China	N/A	2014	running	Thermax Ltd.
30	Germany	Renken Germany / IGLO GmbH	2014	running	Thermax Ltd.
29	China	N/A	2013	running	Ebara
28	Japan	Denka Co. Ltd.	2013	running	Hitachi
27	Japan	GODO Shusei Co. Ltd.	2008	running	Hitachi
26	Japan	KYB Co.	2007	N/A	Hitachi
25	China	Yanshan Petro-chemical Corporation	1999	N/A	N/A
24	China	Yanshan Petro-chemical Corporation	N/A	N/A	N/A
23	China	Yanshan Petro-chemical Corporation	N/A	N/A	N/A
22	Germany	N/A	1998	≈ 2001	N/A
21	Sweden	STORA Papyrus Nymölla AB	1995	N/A	AB KA Ekström & Son / STORA Papyrus Nymölla AB
20	Netherlands	Tata Steel Europe Ltd. (Hoogovens)	1991	N/A	Rinheat OY
19	Germany	N/A	N/A	> 1995	GEA
18	Japan	Japan Ethanol Co. Ltd.	1987	< 1990	Hitachi Zosen Corp.
17	Japan	N/A	1987	N/A	Tokyo Sanyo Electric Co. Ltd.
16	Japan	N/A	1987	N/A	Tokyo Sanyo Electric Co. Ltd.

15	Germany	Stuttgarter Hofbraeu AG	1986	> 1995	GEA / Kawasaki Heavy Industries
14	Yugoslavia	N/A	1986	N/A	GEA
13	Japan	N/A	1985	N/A	Tokyo Sanyo Electric Co. Ltd.
12	Japan	N/A	1985	N/A	Hitachi Zosen Corp.
11	Japan	Tosoh Nanyou	1985	N/A	Hitachi Zosen Corp.
10	Japan	N/A	1984	N/A	Hitachi Zosen Corp.
9	Netherlands	Delamine BV	1984	> 1995	Hitachi Zosen
8	Japan	N/A	1984	N/A	Hitachi Zosen Corp.
7	Japan	Denka Co. Ltd.	1984	2013	Tokyo Sanyo Electric Co. Ltd.
6	Japan	N/A	1984	N/A	Tokyo Sanyo Electric Co. Ltd.
5	Germany	N/A	1984	N/A	GEA / Kawasaki Heavy Industries-Japan
4	Korea	N/A	1983	N/A	Tokyo Sanyo Electric Co. Ltd.
3	Japan	N/A	1983	N/A	Hitachi Zosen Corp.
2	Japan	N/A	1982	N/A	Hitachi Zosen Corp.
1	Japan	N/A	1981	N/A	Tokyo Sanyo Electric Co. Ltd.

4. Overview of the heat transformer applications

This section analyses the cases of application of heat transformers, with respect to the kind of sectors and production processes in which heat transformers have been implemented.

Table 4 shows that 26 (61% of the total) heat transformer installations have been in the chemical industry, four (respectively 9%) installations have been implemented in the food industry, and seven (respectively 16%) in different sectors, e.g. heavy industry and paper industry. For the remaining six heat transformer installations no information about the sector of integration was found.

Generally, heat transformers have been integrated to one production process or to the shifting of heat between different processes. In the case of heat transformer applications integrated in one production process (these are 20 out of 43, i.e. $\frac{3}{4}$ of those installations where details are known, see table 3), the heat transformer is driven by cooling or waste heat of a component of this production process to deliver the upgraded heat to another component of the same production process (e.g. heat transformer application No. 27, see figure 4). This kind of integrated configuration has often been used in distillation processes.

In heat transformer applications shifting heat between different processes the heat transformer is driven by waste heat of one process and delivers the upgraded heat to another

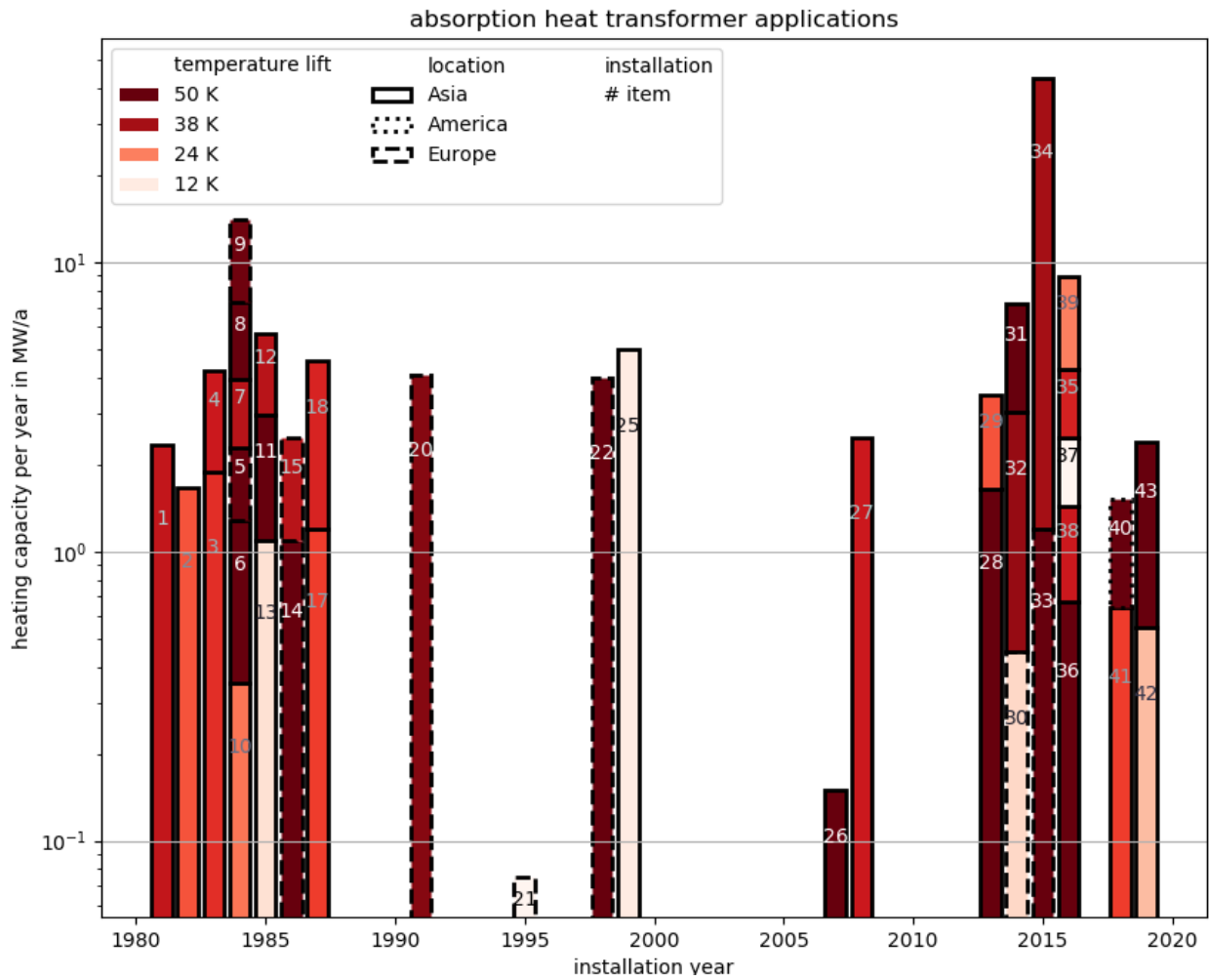


Figure 3: Worldwide heat transformer installations (see items in table 1 and 2)

process or to a central heating network (e.g. heat transformer application No. 26, see figure 5).

More detailed information about the specific application case of the heat transformer could be provided only for 16 installations. This is related to the fact that, due to the close interrelation with the production process, information about the operation of the heat transformer is closely related to confidential characteristics of the industrial product.

Typically, the heat flow \dot{Q}_0 released at the low temperature level T_0 is rejected to the ambient. 12 heat transformer installations make use of cooling towers as the heat sink. Two installations reject the heat flow \dot{Q}_0 to sea water, and one single installation to ground water. Eight installations reject \dot{Q}_0 by means of cooling water, but the heat sinks have not been specified. Finally, for the remaining installations, no information about the heat sink is available.

It is worth highlighting that the heat transformers which reject heat to the ambient air exhibit their maximum capacity during winter; low temperature level T_0 leads to big

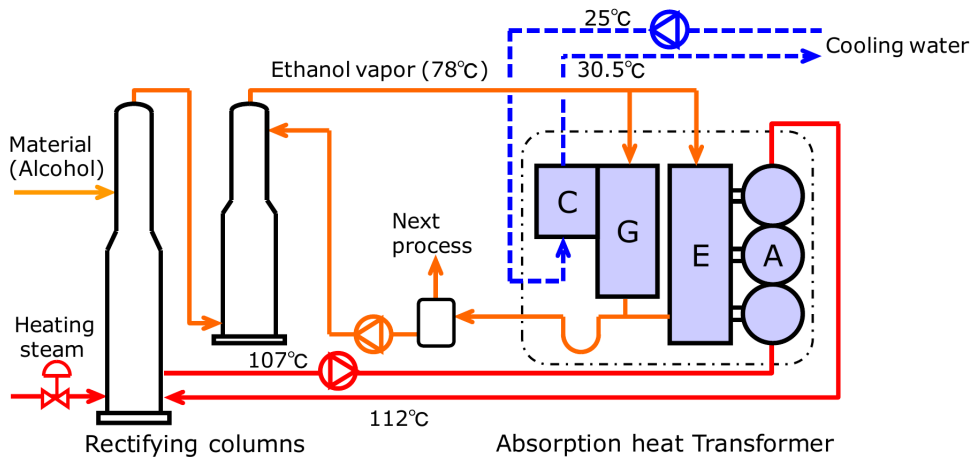


Figure 4: Absorption heat transformer installed in an alcohol distillation plant [38]

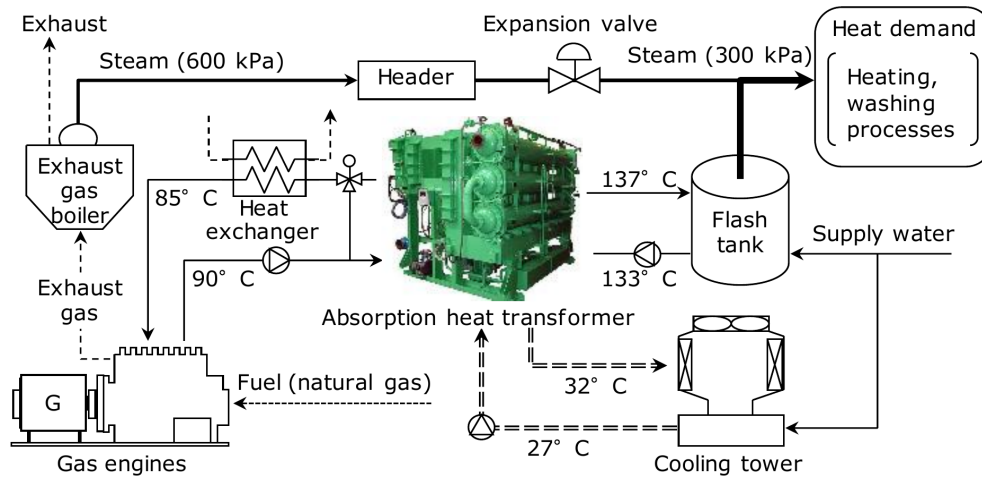


Figure 5: Absorption heat transformer installed in an industrial plant (Capacity: 150 kW) [39]

temperature thrust (see section 1).

Detailed schematic diagrams about the integration of the heat transformer into the production process are available only for the heat transformer installations No. 27, 26, 18, 6 and 1. Especially for heat transformer installations put into operation during the last ten years, detailed information about the integration into the production processes are confidential.

Table 3: Information about the integration into the production process(es) of installations, * marks assumptions

No.	upgraded heat	driving heat	rejected heat	process integrated
43	N/A	N/A	N/A	N/A
42	N/A	N/A	N/A	N/A
41	N/A	N/A	N/A	N/A
40	N/A	N/A	N/A	N/A
39	N/A	N/A	N/A	N/A
38	N/A	N/A	N/A	N/A
37	N/A	N/A	N/A	N/A
36	N/A	N/A	N/A	N/A
35	N/A	N/A	N/A	N/A
34	N/A	N/A	N/A	N/A
33	Hot water (drying process of pasta making)	Waste heat (engine jacket water)	N/A	No
32	N/A	N/A	N/A	N/A
31	Used in the plant	Process cooling for PV cells	Cooling water	No
30	Hot water (vegetable preparation in pre-cooked meal production)	Waste heat (engine jacket water)	N/A	No
29	N/A	N/A	N/A	N/A
28	N/A	N/A	N/A	N/A
27	Heating rectifying column	Latent heat of ethanol/water	Cooling water	Yes
26	Heating, cleaning, drying after painting, and so on	Waste heat from gas engine	Cooling water (cooling tower)	No
25	Hot water (coagulator)	Waste heat (coacervation section)	Cooling water	Yes
24	Hot water (coagulator)	Waste heat (coacervation section)	Cooling water	Yes
23	Hot water (coagulator)	Waste heat (coacervation section)	Cooling water	Yes

22	Steam distribution system	Waste steam (counter pressure turbine)	N/A	No
21	Vapour for effect 1 (higher temperature component)	Vapour from effect 3 or 4 (lower temperature component)	Cooling water	Yes
20	Process steam (several processes at the cold rolling strip mill)	Waste heat (hot rolling strip mill)	Cooling water	No
19	Low press. steam	Waste vapor	N/A	N/A
18	Bottom liquid in distillation	Dis. top vapor	Cooling water	Yes
17	Low press. steam	Alcohol vapour (rectification tower)	Cooling tower	Yes
16	Low press. steam	Alcohol vapour (rectification tower)	Cooling tower	Yes
15	Low press. steam	Waste vapor (evolving during the beer production)	N/A	Yes
14	Low press. steam	Waste vapor	N/A	N/A
13	Low press. steam	Dis. top vapor	Sea water	Yes *
12	Low press. steam	Dis. top vapor	Cooling tower	Yes *
11	Low press. steam	Dis. top vapor	Cooling tower	Yes
10	Hot water	Hot waste water	Cooling tower	No *
9	Low press. steam	Dis. top vapor	Cooling tower	Yes *
8	Low press. steam	Dis. top vapor	Cooling tower	Yes *
7	Low press. steam	Dis. top vapor	Ground water	Yes *
6	Low press. steam	Alcohol vapor	Cooling tower	Yes
5	Low press. steam	Waste vapor	N/A	N/A
4	Low press. steam	Dis. top vapor	Cooling tower	Yes *
3	Low press. steam	Dis. top vapor	Cooling tower	Yes *
2	Low press. steam	Dis. top vapor	Cooling tower	Yes *
1	Low press. steam	Waste steam	Cooling water (sea water)	Yes

Table 4: Information about the production process(es) of installations

No.	production process	sector	ROI [years]
43	N/A	N/A	N/A
42	N/A	N/A	N/A
41	N/A	N/A	N/A
40	Process heating	Food industry	N/A
39	Petroleum industry	Chemical industry	
38	Petroleum industry	Chemical industry	
37	N/A	N/A	N/A
36	N/A	N/A	N/A
35	N/A	N/A	N/A
34	Alcohol production	Chemical industry	N/A
33	Food industry	Food industry	N/A
32	Polycrystalline silicon reduction furnace	Chemical industry	
31	Poly film manufacturing	Chemical industry	N/A
30	Food industry	Food industry	N/A
29	Ammonia production	Chemical industry	N/A
28	Chemical industry	Chemical industry	N/A
27	Distillation plant	Chemical industry	N/A
26	Machinery (hot water for the process)	Miscellaneous	< 4
25	Synthetic rubber	Chemical industry	
24	Synthetic rubber	Chemical industry	N/A
23	Synthetic rubber	Chemical industry	N/A
22	Waste incinerator	Miscellaneous	N/A
21	Pulp and paper mill	Miscellaneous	4.4 to 3.1
20	Strip mill – steel production	Miscellaneous	N/A
19	Chemical industry	Chemical industry	N/A
18	Ethanol distillation	Chemical industry	< 7
17	Ethyl alcohol	Chemical industry	≈ 3
16	Ethyl alcohol	Chemical industry	N/A
15	Brewery	Food industry	N/A
14	Animal carcass	Miscellaneous	N/A
13	Rubber plant (distillation)	Chemical industry	1 to 2
12	Distillation plant	Chemical industry	1 to 2
11	Ethyle amines	Chemical industry	1.7
10	Hot waste water recovery plant	Miscellaneous	1 to 2
9	Ethyle amines plant (distillation plant)	Chemical industry	
8	Rubber plant (distillation)	Chemical industry	1 to 2
7	Rubber plant (distillation)	Chemical industry	1 to 2
6	Ethylalcohol distillation plant	Chemical industry	

5	Animal carcass	Miscellaneous	N/A
4	Distillation plant	Chemical industry	1 to 2
3	Butadiene rubber plant (distillation)	Chemical industry	1 to 2
2	Distillation plant	Chemical industry	1 to 2
1	Butadiene rubber plant	Chemical industry	1

5. Economical overview of heat transformers installations

Heating and temperature boosting are realised at a thermodynamic and accounting cost, which are related to the temperature levels involved. Thermal energy approaching 50 °C is regarded as free, but its final utilization cost accounts for the equipment manufactured and maintained to convert into the target useful effect delivered as an output. The economical essence of the feasibility of heat transformer installations is based on the fact that the heat transformer technology relies on electricity consumption in the order of 1% of the system capacity (1 to 2 orders of magnitude lower than a vapour compression system featuring equivalent capacity) and a temperature level of the driving heat that enables using low grade waste heat rather than the fuel of a boiler providing an equivalent output capacity. These aspects provide possibilities for operative cost reductions and the reduction of the environmental footprint of industrial and commercial heating processes. This section reports general observations and specific examples of economic viability of this technology: the payback periods can be favourable, which seems to be contradicted by the limited implementation of the heat transformers in the market [52]. This becomes explainable when contextualized with the lack of concern about CO₂ emissions, and lack of interest in energy-saving-waste-heat-driven technologies due to the low fuel cost, along with the lack of specialized technical operators able to maintain and certify the reliability of absorption heat transformers, with only some companies that are concentrated in Asia. Enslin (2019) [53] reported a detailed evaluation of the heat transformers first cost, while accounting for design, engineering, commissioning and other costs, as $\approx 20\%$ of the direct cost of the components. Notwithstanding the higher investment cost of ≈ 1500 \$/kW (the reported value is likely overestimated due to the hybrid configurations analysed in [53]), when compared to the reference value of vapour compression systems (≈ 900 \$/kW [54]), it is concluded that the utilization of heat transformers for heat recovery is largely superior to conventional heat pump systems. Buckner et al. (2015) [55] reports a consistent range of investment cost for absorption technology, but a rather lower reference investment cost for vapour compression heat pumps [56, 57, 58, 59, 60] to investigate the maximum acceptable investment cost in relation to the operating hours demand and different consumer types for different heat transformation technologies. In an earlier study, Lee (1999) [61] reports significantly lower investment costs for absorption systems with a capacity of 1750 kW or more. Overall, the economical evaluations reported in literature are optimistic for the market of the heat transformer technology and the return of investment (ROI) gathered from previous literature (table 4) is giving a consistently positive economic outlook of the listed installations (frequently below two years).

Aoyama and Oikawa (2020) [62] quantified the reduction of the environmental footprint

of industrial processes assisted by a heat transformer (figure 6). Comparing a heat transformer with a heat upgrade capacity of 1 MW to the corresponding operation of a gas fired boiler, they identified a maximum reduction of 85 % of the CO₂ emissions at 8000 hours operation per year along with a ROI lower than 2 years. For the studied case, the initial investment cost, which includes the initial cost of the system, auxiliary equipment, installation, electricity, make-up water for the cooling water, and maintenance fee, can be recovered approximately in a 12,000 hour operation.

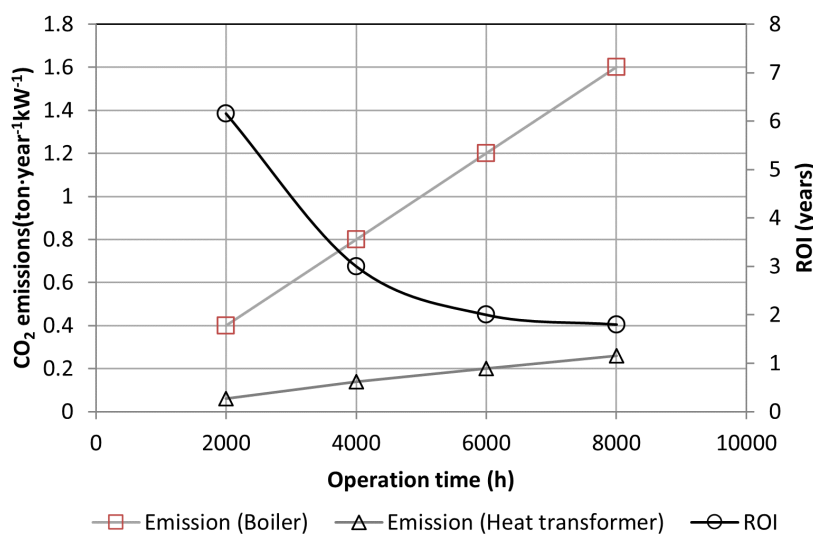


Figure 6: CO₂ emissions and ROI vs operating hours (from [62])

Fujii et al. (2010) [38] describes the thermo-economic effectiveness of the installations No. 26 and 27. The first installation is integrated in the co-generation system of a machinery plant in Japan to replace direct-fired boiler on the steam line for heating demand. The efficiency improvement of the co-generation systems was estimated to be as high as 13.7% (reaching 74.3%). Accordingly, for 8,000 hours of annual operation time, the annual CO₂ emission was reduced by 776.7 tons and the ROI was estimated to be less than 4 years [38]. In the case of the latter installation (No. 27), assuming the boiler efficiency for comparison to be 90% due to its large capacity, CO₂ emissions could be reduced by 12 787 tons/year along with an annual saving in the operation cost of 959.4 k€/year (calculations are reported in table 5).

Ma et al. (2003) [40] reports that the integration of installation No. 25 to the synthetic rubber plant of Yanshan Petrochemical Corporation in Beijing (China) resulted in a substantial reduction of the steam consumption per ton of rubber. The total first cost of 6.1 million Yuan (RMB) is recovered in 2 years when considering equivalent benefit by the steam saving (3.48 million Yuan/year), the cost for electric consumption of the heat transformer (261,000 Yuan/year), and depreciation value (0.424 million Yuan). Additionally, when compared to the equivalent operation of a direct fired boiler, the heat transformer operation prevents the release of 2,337 tons of exhaust gas to the environment, including 104 tons of SO₂, 7 tons of

Table 5: Economical calculation for heat transformer installation No. 27

Boiler operation cost		Heat transformer operation cost	
Boiler efficiency (LHV based)	90 %	Electrical consumption heat transformer	24 kW
Required fuel heat	2.75 MW	Annual consumption	192 MWh/year
Heavy fuel oil LHV	36.3 MJ/L	Electricity price [63]	15.6 ¥/kWh
Annual operating hours	8000 h/year	Electricity cost (B)	2.9952 M¥/year
Heavy fuel oil consumption	272.7 L/h		
Annual fuel consumption	2181.8 kL/year	Total cost reduction (A) - (B)	121.4 M¥/year
Heavy fuel oil price [64]	57 ¥/L	Exchange rate	126.5 ¥/€
Reduced fuel cost (A)	124.4 M¥/year	Total cost reduction in Euro	959.4 k€/year

dust, 22 tons of NO_x , and 0.63 tons of CO.

Kato (1988) [45] reports a detailed cost analysis of the installation No. 17. However, it is considered as a specific case representative of the Japanese market in the late 1980s, with the cost items reported in table 6 [45], which result in an estimated ROI of 1.7 years. The author states that, due to the incurrence into corrosion issues and the substitution of the solution pump, the investment cost was actually recovered in approximately 3 years.

6. Corrosion

Even at low salt mass fractions, a Lithium Bromide aqueous solution is similar to seawater in that it is highly corrosive to common metals and alloys. The corrosive environment in Lithium Bromide solution is particularly intense at high-temperature and with salt mass fractions higher than 60%. In common absorption system applications, mild steel is often used for the construction of the main components. Furthermore, in several cases the concentrated working mixture is heated up to 160 °C. Many studies have been conducted on corrosiveness of working pair $\text{H}_2\text{O}/\text{LiBr}$ and corrosion inhibitors suitable for it in order to ensure durable operation of these systems [65, 66, 67, 68]. In 1964, with the support of the American Gas Association, investigations on corrosion of mild steel due to concentrated Lithium Bromide aqueous solution in high-temperature (up to 185 °C) was conducted by TRACOR [69].

The amount of Hydrogen generated, weight change of steel slabs, and surface corrosion products were investigated, and it was found that an oxidation film of Fe_3O_4 is initially formed on the steel surface in an alkaline Lithium Bromide aqueous solution in a short time, slowing down subsequent corrosion; the benefits of alkali pre-treatment are also discussed. Accordingly, various corrosion inhibitors have been tested for practical use.

Table 6: Heat transformer No. 17 investment costs (from [45], in Japanese)

Category	Equipment	Fee [x 1000 ¥]	Remarks
Fixed cost	Heat transformer equipment fee	170 000	Installation and auxiliaries
Operation cost	Electricity fee	6400	20 ¥/kWh (40 kWh x 8000 h/year)
	Make-up water fee	3200	50 ¥/m ³ (loss 2%) (400 m ³ /h x 0.02 x 8000 h/year)
	Maintanance fee	2550	1.5 % of heat transformer equipment fee
	Insurance	850	0.5 % of heat transformer equipment fee
	Tax	2380	1.4 % of heat transformer equipment fee
	Labour	7000	Management, other
Energy saving	Steam value	140 640	Annual fixed costs 17 000 Capital interest rate: 0.102 96 Interest: 6 % Lifetime: 15 years
			3000 ¥/ton (5.86 ton/h x 8000 h/year)
ROI	1.7 years		

- Lithium Chromate (Li_2CrO_4) is an effective corrosion inhibitor and does not require pre-treatment of the sorptive solution. However, it does not exclude pitting corrosion, exhibits limited compatibility with surfactants such as octyl alcohol, and is poisonous. Although its use has never been banned, as its handling and disposal requires expensive and risky procedures, results of pioneering studies exploring its replacement with Lithium Molybdate (Li_2MoO_4)[65] were presented by the Sanyo Electric Co., Ltd. at the domestic symposium of the Japanese Association of Refrigeration in 1990; since 1997, commercial systems have effectively replaced this inhibitor [70].
- Before Lithium Chromate was replaced, among other corrosion inhibitors, Bismuth Oxyacid + Li_2CrO_4 was identified as a viable alternative by Motor Manufacturing Co. Ltd, in 1968 [65].
- Unlike Lithium Chromate, Lithium Molybdate (Li_2MoO_4) is an effective corrosion inhibitor that prevents pitting corrosion in carbon steel and is not poisonous. However, given its low solubility, pre-treatment of the solution is necessary for ensuring proper mixing and surfactant mass fraction.
- Further, Lithium Nitrate, Lithium tungstate, phosphomolybdic acid, and ruthenium

salt, are also said to have a substantial effect for suppressing corrosion [65].

In [71] different commercial materials and corrosion inhibitors are analysed regarding their suitability for the application in triple effect absorption chillers. Here, probes of commercial materials in Lithium Bromide solution in combination with corrosion inhibitors were tested in test tubes for one specific working condition ($T \approx 200\text{ }^\circ\text{C}$, $p \approx 0.28\text{ MPa}$). There were no investigations about the dependency of corrosion from the temperature. Stainless steel was identified as promising material for the generator of triple effect chillers. Furthermore, it was confirmed that, for mild steel, using Lithium Molybdate as the corrosion inhibitor provides low corrosion rates.

The Japanese governmental organization NEDO conducted a three-year project on the development of triple effect absorption chillers between 2001 and 2003. In order to soundly verify the feasibility of absorption systems operating at high temperature, common technical issues like corrosion were assessed on different prototypes from four participating manufacturers (Hitachi Industries Co. Ltd., Yazaki Corporation, Kawasaki Thermal Engineering Co. Ltd. and Daikin Industries Ltd.) and Japan Gas Association [72, 73, 74]. Common evaluation techniques developed by the Japanese Gas Association were adopted in parallel by the four manufacturers to build a consistent and comprehensive database for establishing a suitable pair of material and inhibitor additive in combination with aqueous Lithium Bromide solution. The material-inhibitor pair (carbon-steel and Li_2MoO_4) went through electrochemical testing, autoclave testing, generator model testing (see figure 6), and actual machine testing. The influence of the operative temperature, Lithium Bromide mass fraction, Li_2MoO_4 mass fraction, clearance between two active solid interfaces, surface treatment, and operating time were investigated.

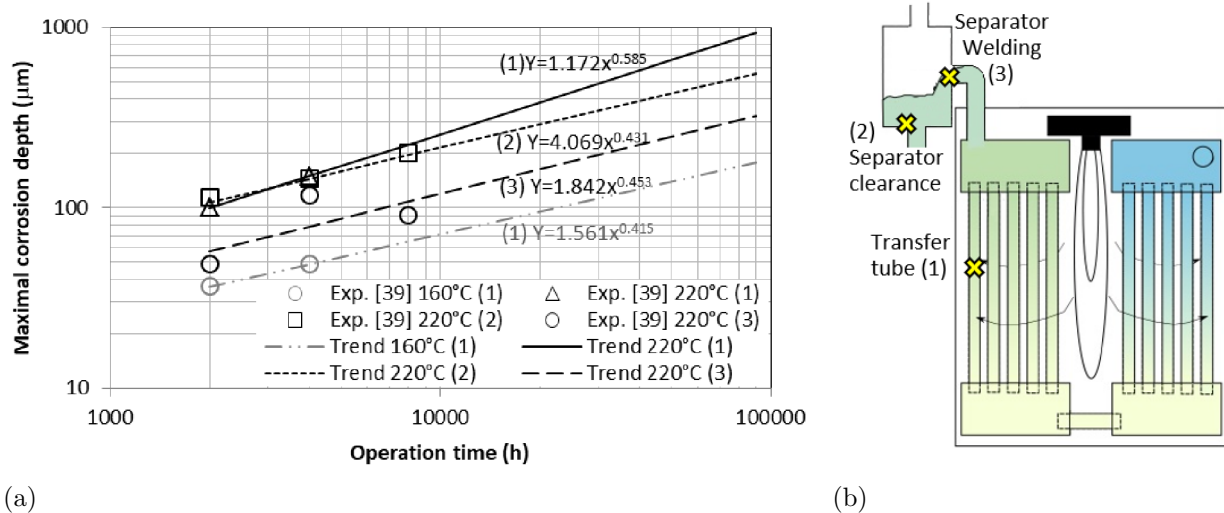


Figure 7: Maximum corrosion depth vs operation time (a), within a "generator model" (b) [74] test section at three different reference locations, (1) Transfer tube, (2) Separator clearance, (3) separator welding

The combined results of tests confirmed that the inhibitor would ensure effective anti-

corrosion properties even at the operating temperatures encountered in a triple-effect system ($< 250\text{ }^{\circ}\text{C}$), if mass fraction of the inhibitor is properly controlled (source NEDO report, 2003 summary). However, special care should be taken when the operating temperature is above $165\text{ }^{\circ}\text{C}$. Additionally, in a more recent work [75] showed the effectiveness of Po-Mo (an organophosphonate plus Sodium Molybdate) as a corrosion inhibitor in 55% Lithium Bromide at $240\text{ }^{\circ}\text{C}$, with maximum corrosion rates as low as $25\text{ }\mu\text{m}/\text{year}$.

Figure 7 illustrates the data measured by the Japan Gas Association at three different locations of the generator model test sections (see figure 7(b)): (1) transfer tube, (2) separator clearance, and (3) separator welding. It is worth noting that, for operation time beyond 8000 hours, the trend-lines estimated by extrapolating the experimental data in figure 6 are considered to be overestimating the maximum depth of corrosion experienced during real operation. This is due to the gradual oxidation of the exchange surface, where the formation of Fe_3O_4 reduces the electrochemical potential driving the occurrence of corrosion. Accordingly, as the corrosion rate is expected to slow down as the operation time increases, the trend-line extrapolating the experimental data in figure 7 is obtained through exponential power laws. The operating conditions for triple-stage absorption chillers are, in fact, significantly more restrictive than the operative conditions encountered in single-effect or double-lift heat transformers. The high temperature generators of multi-stage absorption chillers are often directly fired by the exhaust gas obtained from combustion of natural gas or similar fuels. Therefore, within compact system configurations, there may be areas of the surfaces in contact with the aqueous Lithium Bromide solution which will substantially exceed the design saturation temperature of the solution. Conversely, the high temperature absorber in a double-lift heat transformer will provide a quite homogeneous excess temperature required for the generation of pressurised steam or the achievement of the target temperature of the substance recovering heat from these systems.

7. Crystallization

Crystallization of aqueous Lithium Bromide solution in heat transformers leads to the blockage of pipes, heat exchangers or even pumps. Accordingly, operation normally stops by itself (flows break down) or must be interrupted to locate the crystallized solution and decrystallise it. Commercial heat transformers include technical protection against crystallization. [76] presents a general discussion about crystallization in absorption chillers and heat pumps.

Generally, the risk of crystallization of aqueous Lithium Bromide solution during operation is lower for absorption heat transformers than for absorption heat pumps / chillers, because the operative solution temperature level is higher for the first (see figure 8). Nevertheless, for heat transformers operating with high driving heat temperatures corresponding to low heat rejection temperatures, the risk of crystallization emerges due to the correspondingly higher operating concentration.

Accordingly, as the solution might be more concentrated in heat transformers, there is a significant risk of crystallization in shutdown periods, when the solution cools down to

ambient temperature. This is especially dangerous because heat transformers are usually installed outdoors. Therefore, dilution routines for shutdown are indisputably necessary.

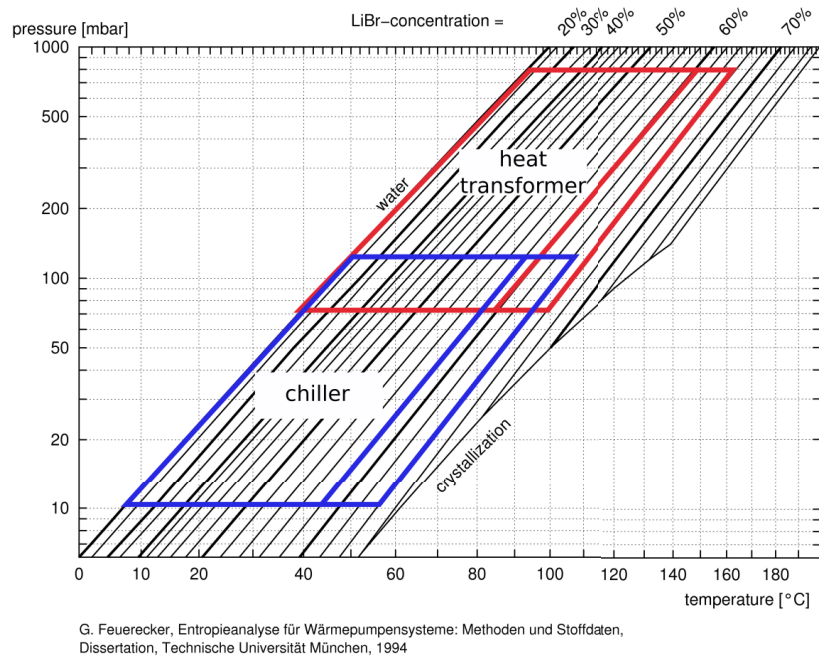


Figure 8: Comparison of heat transformer and heat pump process regarding crystallization risk

Wherever the working conditions yields a high crystallization risk, i.e. for heat source temperatures about 100 °C or higher, the design can be changed to a double-lift cycle. The process then works with a rather dilute solution, however, the COP will be essentially reduced from roughly 0.5 to roughly 0.3.

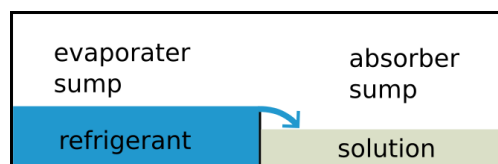


Figure 9: Scheme of refrigerant overflow crystallization protection

Technical protection against crystallization during operation can be put into effect by refrigerant overflow from the evaporator to the absorber (see figure 9). If due to some change in operation, the solution becomes too concentrated, the amount of water in the sump of the evaporator will increase above the design level. The refrigerant then flows into the absorber and reduces the Lithium Bromide mass fraction again. This technical solution is stable and does not need an active control system. However, overflow of refrigerant from the evaporator to the absorber is an internal loss, which decreases the COP. A more flexible, but active control would modify the working conditions, e.g. by increasing the heat rejection

temperature T_0 or decreasing the driving heat temperature T_1 . However, this reduces the heating capacity. A more general overview of possible approaches to avoid crystallization in absorption heat pumps is described in [76, 1325–1337].

8. Non-condensable gases

Generally, aqueous Lithium Bromide absorption cycles operate below atmospheric pressure. This creates a possibility for infiltration of air. Additionally, corrosion can lead to generation of gas, especially Hydrogen. Notwithstanding the fundamental necessity of avoiding concentration of non-condensable gases, there is little established knowledge about their behaviour and localization within the cycle. Therefore, only few experimental [73], [74] and numerical studies ([74], Suzuki [77]) have been presented in the related literature. Even if a small fraction of non-condensable gases enters the system, a drastic reduction of the transfer performance of falling film devices (and consequently, the whole cycle) is experienced while accelerating the progress of corrosion. Therefore, reliable airtightness along with an effective method for discharging non-condensable gases [65] is a standard requirement. Since the condenser is the component with the lowest pressure within heat transformers, non-condensable gases collected at this component are the most harmful for the system capacity, whereas those located in the absorber causes the intensification of corrosion.

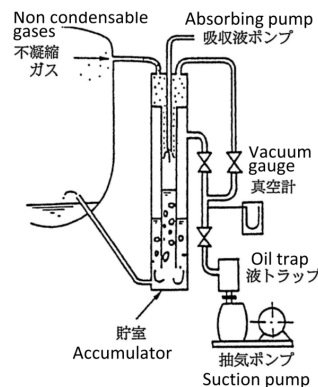


Figure 10: Motor-driven vacuum pump for purging non-condensable gases (related to [65])

First generation absorption systems were commonly equipped with vacuum pumps, that were periodically operated to perform a purge of these non-condensable gases (see Figure 10). However, as mist from the system mixes with the oil, maintenance of the lubricating oil of the pump is required. On the one hand, the tightness of the machine itself has improved along with the expertise gained over time for this type of purge systems. On the other hand, gaseous Hydrogen is internally generated due to the corrosiveness of aqueous Lithium Bromide, and mostly occurs when the operation starts after commissioning. As this phenomenon occurs, the thin layer of Fe_3O_4 on the solid walls decreases, and if the amount of internally generated gas stays small, it can be effectively separated from the heat transfer section to a separate chamber, where purging devices can be installed. From there they are most commonly discharged by a vacuum pump or water ejectors. Multiple

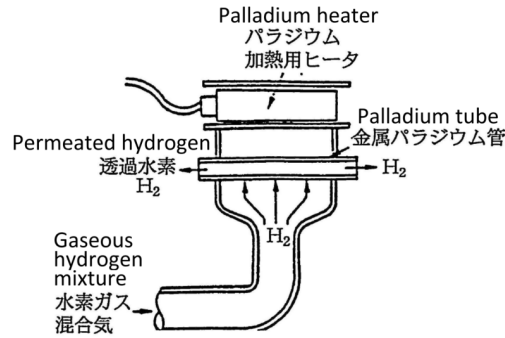


Figure 11: Palladium cell for purging non-condensable gases (related to [65])

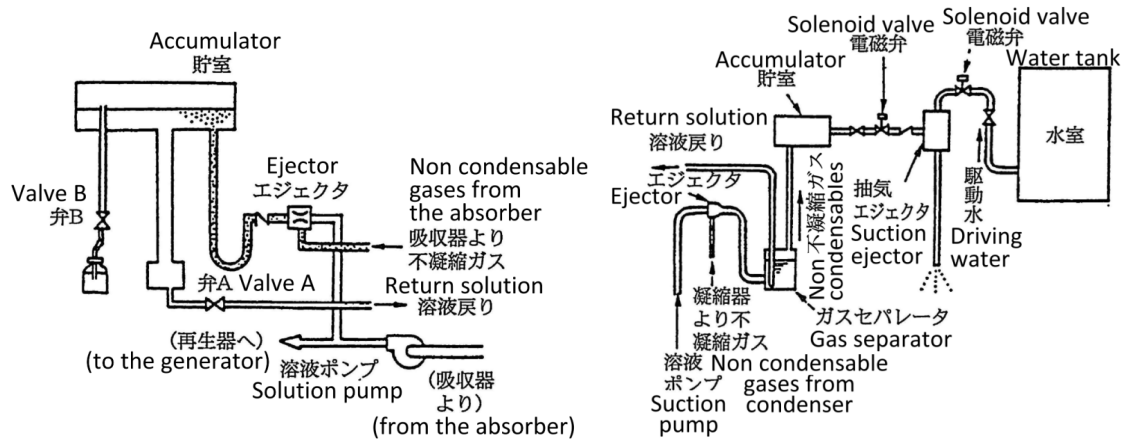


Figure 12: Solution ejector and water ejector for purging non-condensable gases (related to [65])

other motor-less purging devices have been patented, providing alternative methods for the extraction of non-condensable gases. Currently, available options [65] include:

- The Palladium cell method (see figure 11) [65] [78]: In the palladium cell system, a palladium tube is heated by an electric heater, allowing Hydrogen in the system to pass through its walls and discharging it out of the system. However, since it is only effective for Hydrogen, and due to the high cost of the Palladium, this approach is currently not implemented in commercial systems. Nevertheless, it would be important in cases where Hydrogen is internally produced and has a risk for explosion in the purge chamber or during purging.
- The solution ejector (eductor) method [79]: At present, ejectors driven by the circulating solution (see figure 12) [65] are the most conventionally employed gas separation method in commercialised systems (Hitachi and Ebara). This method can be used to extract non-condensable gases and deliver them to a separation chamber, where they do not affect heat and mass transfer.
- The water ejector method [65] [80] (see figure 12): Water ejectors and steam ejectors can be used as purging devices for discharging non-condensable gases outside the

machine. Since these gases usually stagnate in the condenser chamber, refrigerant ejectors have been patented [65][81] to directly discharge the non-condensables from the condenser while avoiding the contamination of the refrigerant by the solution. The steam used for driving the ejector is a part of the vapour generated by the driving heat input to the system, whereas the water is a part of the cooling water. Because steam and water are continuously extracted, they need to be continuously reintegrated in to the heat transformers.

9. Process control

Modern absorption heat transformers include a microprocessor based control unit that is responsible for different tasks:

- Automatic start up and shut down procedures.
- Safe operation.
- Achieving pre-designed set points and
- Achieving additional goals such as high COP or small electricity consumption (when using advanced control strategies)

To automatically run start up and shut down procedures, the system control must decide when to start and stop the solution and refrigerant pump(s).

In typical working conditions, the pressure difference between the low and high pressure level is larger in absorption heat pump type II than in type I, and can reach up to 1 bar (see figure 8). The pressure difference in absorption heat transformer processes cannot be covered by the use of U-bends (see figure 2) as often used in absorption chillers. Therefore, a manual or automatic valve is used instead. For heat transformer applications in chemical processes, such as distillation, the working conditions are fixed; hence, a simple solution such as an orifice could be used. In most of the heat transformers, however, a motor valve is installed. During the start up procedure, the position of the valve is adapted; after reaching steady state conditions, the position of the motor valve will be fixed. In the case of variable working conditions, e.g. changing cooling water temperature, the position of the valve has to be adjusted and standard motor-driven valves are commonly used. The valves are controlled by the level of the aqueous solution in the sumps below the heat exchanger tubes.

If the solution pump is not controlled, the solution flow rate from generator to absorber during start up and shut down procedures will be higher than during operation at nominal working conditions, and much higher than the solution flow rate from absorber to generator. As a consequence, the solution pump should then be switched on and off, to avoid cavitation and dry operation of the pump. This can lead to unstable operation of the heat transformer. This is also a known problem in solution circulation in double-effect absorption chillers. The relationship between the pressures at the absorber and the generator of the single-stage heat transformer in figure 8 is almost the same as the relationship between the

high-temperature generator and the low-temperature generator of the double-effect absorption chiller. Furthermore, this relationship fluctuates significantly, even for small variations in the temperatures.

There are different ways to avoid this mismatch of the solution flows, which can be mainly classified into two categories: (1) Outflow control and (2) Inflow control of high-temperature generator for chillers (absorber for heat transformers).

With Outflow control (1), the inflow to the high-temperature generator is almost constant (an orifice that equalises the flow rate is provided in the pump discharge line). A controlled valve (float valve or motor valve) is installed on the outflow line. To ensure solution circulation even when the pressure of the high-temperature generator is low, the valve will open with decreasing pressure. If this is not sufficient, the solution pump needs to be switched ON and OFF.

With Inflow control (2), the return line from the high-temperature generator has an orifice or throttle that ensures that for the nominal conditions, the designed flow rate is obtained. The inlet flow to the high-temperature generator is controlled by changing the rotational speed of the pump (by a variable speed driver) or using a controlled valve (usually a float valve) after the solution pump valve. The flow rate will change depending on the pressure conditions.

As the additional motorized controlled valve required by method (1) for a common range of pressure ratios is more expensive than the VSD required for method (2), the latter results to be cheaper than method (1). Furthermore, in method (2), for low loads, the circulation rate decreases with decreasing pressure in the high-temperature generator, thereby helping to ensure efficiency. Currently, almost all two stage chillers use Inflow control. Figure 13 shows the two alternatives applied to a heat transformer.

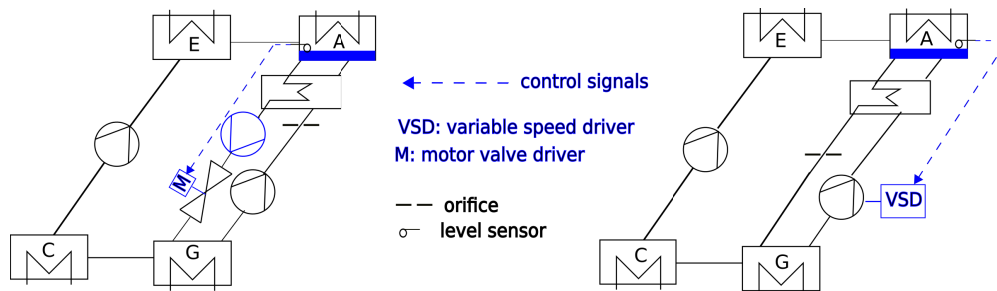


Figure 13: AHT absorber solution Outflow control (left) or absorber solution Inflow control (right)

Since the advantages of the Inflow control are also valid for heat transformers, this method is also the preferred one for them. An orifice that adjusts the design flow rate is included in the path from the absorber to the generator. By controlling the rotational speed of the pump or an additional valve, the solution flow rate can be adjusted for matching the outflow entering the absorber.

Additional solutions are needed for multi-stage heat transformers with serial solution flow where the low temperature absorber receives solution from the high temperature ab-

sorber. During start up, when the heat source heats up the low temperature evaporator, the pressure of the high-temperature absorber does not increase. First, the solution needs to reach the low temperature absorber to start refrigerant vapour absorption from the low temperature evaporator in order to transfer heat to the high temperature evaporator. Then, the refrigerant at the higher pressure vessel is heated and the pressure of the high temperature absorber starts to rise. Because of this, a mechanism that helps the solution to enter the low-temperature absorber is required. Some patents have been developed (for example, [82]) with designs that incorporate some elements of parallel flow into the series flow between absorber and generator. In addition to controlling the amount of inflow into the high-temperature absorber, a fraction of the solution that flows to the high-temperature absorber is bypassed by using an additional orifice so that a small amount of solution can be introduced into the low-temperature absorber. (A solenoid valve may be used instead of the orifice).

As for any other type of absorption heat pumps, crystallization must be avoided. In order to do that, either passive or active anticrystallization methods can be used. When using active methods to avoid crystallization, the control system modifies the external temperature levels or internally bleeds refrigerant to the solution by means of a valve opening depending on the measured mass fraction of the solution.

For load adjustments and to control the revaluated heat flux and revaluated temperature, methods developed for the control of absorption chillers are widely used. The main difference between a heat transformer and a chillers is that most heat transformers are designed for a specific operation condition that is not expected to change significantly during operation. However, most absorption chillers have a variable cooling demand, which is usually dependant on the ambient temperature and changes significantly during the year.

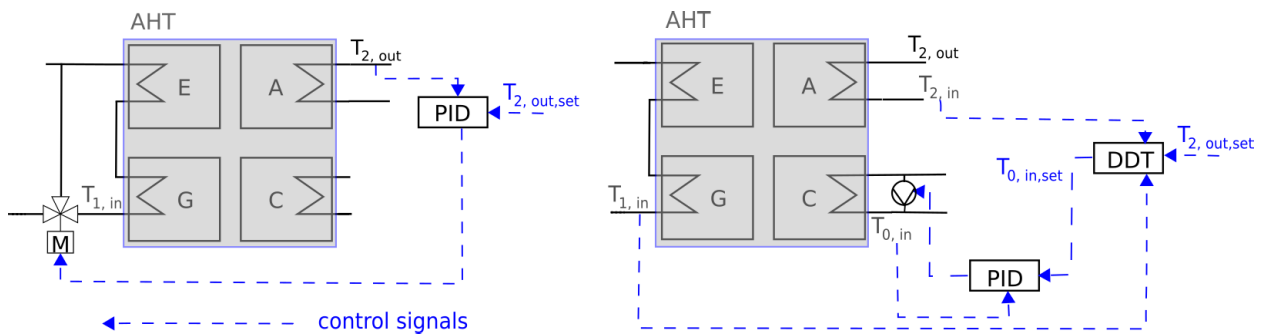


Figure 14: Driving stream temperature control (left) and DDT-cooling water temperature control (right) for a constant revaluated temperature

Manufacturers use a control strategy for load adjustment that controls the volume flow rate of the heat carrier of driving heat depending on the outlet temperature of the heat carrier at the absorber of revalued heat (see figure 14 top). An analogous strategy is often used for absorption chillers and heat pumps, and is the most widely used method for capacity

adjustment [83] [84].

An alternative to the driving heat control strategy is cooling water control strategy, which actively controls the cooling water inlet temperature provided by the heat rejection system. For example, Albers [85] has presented strategies using a predictive controller based on the characteristic equation method to calculate the cooling water needed for a given operation point. This strategy reduces the operation cost by controlling the cooling water temperature and reducing the auxiliary energy requirement of the heat rejection system. Advanced control strategies combine driving heat and cooling water control strategies to minimize cost functions, such as, primary energy consumption or operation costs.

Similar control strategies can be developed for heat transformers (see figure 14 bottom) based on the characteristic equation of a heat transformer [27], which has been investigated in the European research project Indus3Es [86]. For example, some of these strategies aim to increase the temperature of the cooling water coming from the heat rejection system, and thus reduce the total amount of parasitic energy needed by the system.

10. Heat and mass exchanger

In early heat transformers falling films on either horizontal (see figure 15) or vertical (see figure 16) tubes were used. However, at present, heat transformers mainly use horizontal heat exchanger tubes (see figure 17, 18, 19).



Figure 15: Heat transformer installed in 1986: GEA, nominal capacity ≈ 1.4 MW [46]

In addition, at present, position of the heat exchanger relative to one another is different depending on the manufacturer's preferences. If manufacturer is Ebara, the absorber is positioned above the evaporator (see figure 17); however, when the manufacturer is Hitachi, the absorber is split into three vessels piled one above the other and connected to the same one evaporator, which are positioned next to the evaporator, generator and condenser (see figure 18).

The heat transfer mostly occurs at the solid-liquid interface, whereas mass transfer is realised at the vapour-liquid interfaces; both these occurrences take advantage of larger ratios of wetted areas of the outer surface of the tubes. In this respect, a uniform spreading of the liquid along with low film thickness is to be ensured with a suitable distribution



Figure 16: Heat transformer installed 1982: Hitachi Zosen Corp., nominal capacity ≈ 1.7 MW [51]

device for maximising transfer interfaces and minimising transfer resistances. Similar to heat pumps and chillers, dripping type or spraying type liquid distributors are conventionally employed. *Spraying* type distributors (e.g. Ebara system designs; [87]) are inexpensive nozzles employed for achieving more compact staggered-tube heat exchanger configurations; liquid atomization through the nozzle is beneficial for enlarging absorption interfaces to improve adiabatic absorption and lower sensitivity to deviation in levelling. *Dripping* type distributors are generally known to have a more effective liquid distribution, i.e. lower dispersion of liquid droplets and contamination between adjoining vessels, better longitudinal distribution, and less tendency for blockage by rust or dirt. Hitachi and Thermax heat transformer devices rely on a dripping type distributor, which realises favourable and stable liquid distribution even when placed in an oblique position and is able to operate for a long term without blockage (e.g. Hitachi system design; patent US 6,253,571 [77]).

11. Surfactants

A particularly effective way to enhance the transfer performance of absorption systems and consequently, reduce size and cost, is the adding of small fractions of surfactant additives. Saturated chain and branch alcohols having 6 to 8 carbon atoms in the chain have been extensively tested and implemented in absorption machines. Their beneficial effect is particularly obvious in terms of improved wetting and absorption rates. Hihara and Saito [88] showed that, when 2-Ethyl-1-Hexanol was added to aqueous Lithium Bromide solution, the absorption rate was 4-5 times higher than the corresponding operation without additive. This cannot be explained solely by the improved surface wetting. In these circumstances



Figure 17: Current heat transformer: Ebara, nominal capacity ≈ 7 MW, A: Absorber, G: Generator, E: Evaporator, C: Condenser (All Rights Reserved, Copyright Ebara Refrigeration Equipment & Systems Co., Ltd. 2019)

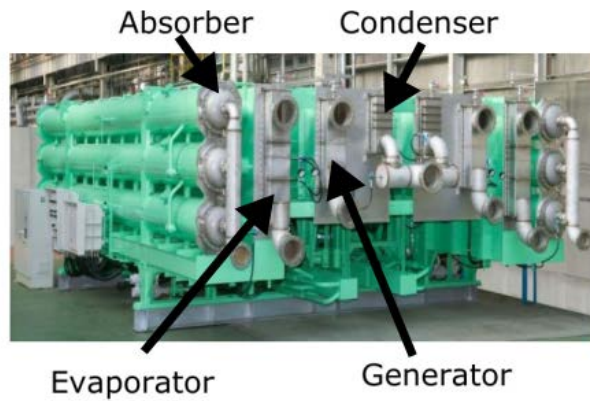


Figure 18: Current heat transformer: Hitachi, nominal capacity ≈ 2.5 MW, (related to [38])

the absorptive solution experiences an intense interfacial turbulence causing rapid and continuous mixing of the solution (Marangoni convection). Among the additives tested [89], 2-Ethyl-1-Hexanol, 1-Heptanol, and commercial FC-171 offered the best performance for high temperature systems in terms of absorption enhancement and thermal stability. Tests conducted at a high operating temperature, on the range of single-effect and double-lift heat transformers, (see figure 20 from [90, 91, 92] source Report NEDO, 2010-2012, [93]) have also demonstrated a substantial enhancement [90, 91, 92].



Figure 19: current heat transformer: Thermax, nominal capacity ≈ 1.2 MW, (All Rights Reserved, Copyright Thermax Ltd. 2019)

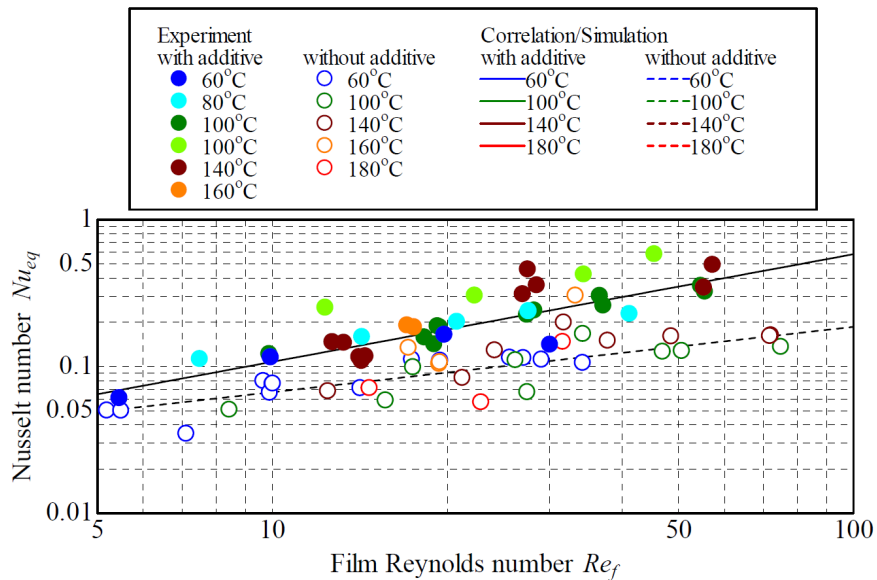


Figure 20: Measurements of heat transfer coefficient of aqueous Lithium Bromide in a falling film test section at high temperature with and without surfactant additives from [90, 91, 92] (source Report NEDO, 2010-2012)

Accordingly, operative heat transformers' installations feature surfactant additives, specifically, 2-Ethyl-1-Hexanol. Although direct estimations of the capacity improvement related to surfactant additives for heat transformers are lacking in literature, their implementation is a customary practice which is recognised to be important for a compact design and a high efficiency of the systems.

12. Technology overview

Although a lower COP is often cited as a major hindering factor for the spreading of this technology, due to the low exergetic level of the driving energy sources and the commonly biased comparison between thermal and electric COP, this statement is inaccurate and unrelated to the economic feasibility of the system.

In light of the discussion reported in this work, this section summarises the advantages and disadvantages of the absorption heat transformer technology and attempts to interpret the main reasons for the limited implementation cases of this technology.

12.1. Advantages

The following beneficial characteristics can be stated:

- Almost negligible electricity consumption compared to conventional electricity driven vapour compression systems and no direct fossil fuel consumption results in lower CO₂ equivalent emissions over the operative lifespan of the system;
- lower operating cost than conventional alternatives;
- the use of natural refrigerants as circulating working fluids further reduce the system environmental impact with no direct CO₂ equivalent emissions compared with vapour compression systems not using natural refrigerants;
- having pumps as the only system components with moving parts result in lower maintenance cost than vapour compression systems with fast moving parts, such as the compressor. The less frequent operation interruption also results in longer system life expectancy [94];
- larger output capacity with lower heat sink temperature and no substantial performance drop at part load operation represent strategic advantages when compared to the operation of equivalent vapour compression systems;
- temperature upgrades up to higher temperatures than the present state-of-the-art of vapour compression systems (up to 165 °C without special maintenance care for preventing corrosion);

12.2. Disadvantages

Despite the above-mentioned thermo-economically and environmentally strategic characteristics, the implementation of absorption heat transformers has suffered several technological challenges and disadvantages with respect to conventional heating technologies:

- large exchange surface requirements makes the technology bulky and heavy;
- a higher investment cost which requires good (expensive) planning for profitable operation;

- special measures for reducing the risk of corrosion at temperatures higher than 165 °C are required;
- the rigorous tightness requirements of the sub-atmospheric operation pose an issue during long inactive periods without maintenance when the purge mechanism is inactive;
- long response times pose a problem for quick operation adjustment to dynamic loads (of the time scale of seconds-to-minutes);

13. Conclusion

In the last 38 years 48 absorption heat transformers were installed in 43 installations with a total capacity of ≈ 134 MW. At present, 17 installations are operational. One heat transformer has been operational for the past 11 years. In another site, a heat transformer was in operation from 1984 to 2013; due to favourable experience, the initially installed heat transformer was replaced in 2013. Two main installation periods have been highlighted: from 1981 to 1987 and from 2013 to present. Nearly 74 % of the installations are placed in Asia, approximately 23 % are in Europe, and only one installation is in America.

Approximately 61 % of the heat transformer installations were applied to the chemical industry, 9 % to the food industry and 16 % to different sectors, e.g. heavy industry and paper industry, while no information about the applied sector is available for 14 % of the installations.

Approximately 74 % of the heat transformer installations were integrated into one production process. Only 1/4 of the heat transformer installations were driven by the heat of one production process and supply the upgraded heat to another/other process(es).

The most typical applications are the integration into distillation columns of chemical processes (process integration) and the production of hot water and low pressure steam (heat recovery from one process and use in another process). In the first case, the condensation heat of the product leaving the distillation columns is the driving heat for the heat transformer while upgraded heat is used to reduce the energy consumption of the reboiler at the bottom of the column. In the second case, the driving heat is obtained from process cooling or condensation of process steam. The benefits of these applications are both economic and environmental. For typical sizes of the upgraded heat flow between 1 and 5 MW, the emission of several thousand tons of CO₂ per year can be avoided. The operational savings are in the range of several hundred thousand euros per year, resulting in ROI values between 1 and 4 years.

The COP for a typical industrial application of the heat transformers is $COP \approx 0.47$. As only water/Lithium Bromide is being used since 1998, this working pair can be considered as the state-of-the-art of commercial heat transformers. Safe and sustainable operation boosting heat up to 165 °C is demonstrated as the state-of-the-art when the concentration of the corrosion inhibitor Li₂MoO₄ is properly maintained. Boosting to higher temperatures is possible, but a higher maintenance effort is needed. The surfactant 2-Ethyl-1-Hexanol is used in current heat transformers to improve the transfer capacity, thereby, reducing size

and cost.

The non-condensable gases are commonly collected in a separation chamber by an ejector from the condenser so that the heat and mass transfer are not affected. From there, they are most commonly discharged by a vacuum pump or a water ejector driven by the cooling water. In current installations, the temperature of the reevaluated heat is controlled by the mass flow rate of the heat carrier of the driving heat, but a more advanced controlling strategy based on the characteristic equation method is also possible. Furthermore, at present, the heat and mass exchangers are made of horizontal tubes, falling films are used for the absorber, evaporator and generator.

This work represents an effort in comprehensively outlining and discussing the established knowledge about the absorption heat transformer technology to propel its development and the related academic discussions. In the future, an open database expanding the information presented in this study about heat transformer installations will help this technology to penetrate the market and will maximise the benefits of this clean energy conversion solution.

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