

Chapter 2

Mass and Heat Exchange Analysis of the Absorption Processes: The Divided Device Method

2.1 Heat Exchange Analysis of Isobar Absorption Processes with Gliding Temperature

The coabsorbent cycles, described in the next chapters, have typical absorption technology processes, of desorption, generation, resorption and absorption. Generally, they will be named absorption processes. These take place usually on large temperature intervals, or simpler, operate with gliding temperatures. In this paragraph we shall present a method to be used in the heat exchange analysis of an absorption process with a source which this is thermally interacting with. Prior to do it we shall consider a single process from the viewpoint of its constitution mass and heat transfer. This aspect will be detailed in [Chap. 9](#). At this moment we only anticipate that a current of mass can couple with a heat current, in order to generate a coupled process of mass and heat transfer, with phase change. In this case, the two currents are influencing reciprocally. On the contrary, in a noncoupled process of mass and heat transfer, the two currents do not influence reciprocally and the resulting process is not changing the phase and is characterized by a heat transfer only. The absorption processes belong to the coupled transfer category, with a complex heat exchange named next also “latent”, while the absorbent or source fluid cooling/heating phenomena, taking place without phase change, belong to the “sensible” heat exchange category.

There are three types of thermal interactions occurring in a coabsorbent cycle:

- (a) latent-sensible, or coupled-noncoupled mass and heat transfer, like, for example, that occurring between an $\text{NH}_3\text{--H}_2\text{O}$ absorbent absorbing NH_3 vapor and the cooling water which takes over the heat released by the former fluid;
- (b) latent-latent, or coupled-coupled mass and heat transfer, like, for example, that occurring between an $\text{NH}_3\text{--H}_2\text{O}$ absorbent absorbing NH_3 vapor and the $\text{NH}_3\text{--H}_2\text{O}$ absorbent generating NH_3 vapor; in this particular case, the former fluid releases heat which is taken over by the latter fluid in a recovering way, in order to generate useful NH_3 vapor within an overlapped temperature glide;

- (c) sensible-sensible, or noncoupled-noncoupled mass and heat transfer, like, for example, that occurring in a low concentration $\text{NH}_3\text{--H}_2\text{O}$ absorbent subcooling process, when the fluid releases its sensible heat to a high concentration $\text{NH}_3\text{--H}_2\text{O}$ absorbent which receives this heat in a recovering preheating way, but without changing its phase.

A spontaneous (natural) heat exchange is conditional upon the simultaneous fulfillment of the followings events:

- i. there is a thermal capacity match between the fluids exchanging heat, or, in other words, the capacity of the former fluid to release (receive) heat equals that of the latter fluid to receive (release) heat;
- ii. the temperature of the fluid releasing heat is always higher than that of the fluid receiving heat with a certain temperature pinch.

To monitor and design a heat exchange means to check the consistency of the conditions (i) and (ii) fulfillment in each reasonable large interval of temperature throughout the thermal process at hand. The most working combinations in the absorption technology, not all, are binary (e.g. $\text{NH}_3\text{--H}_2\text{O}$, $\text{NH}_3\text{--LiNO}_3$, $\text{NH}_3\text{--NaSCN}$, $\text{H}_2\text{O--LiBr}$). A (c) heat transfer of subcooling-superheating type occurs usually in non-equilibrium conditions, at constant pressure and concentration ($p = \text{const.}$, $y = \text{const.}$), and the process suffers a temperature glide, only. In this case, the check of the (i) and (ii) conditions fulfillment is simpler. An experienced designer doesn't need even to perform this check, it calculates directly the preheated absorbent outlet temperature based on the knowledge of the input parameters of the subcooled and preheated absorbents. However, this is not the case of the heat exchange of the (a) type and so much more of the (b) type, when the systematic check of the (i) and (ii) conditions fulfillment is mandatory. In this case, even in the simplest situation, of the isobar processes, the heat exchange becomes complex. Indeed, this time the binary fluids are two-variant, so, if the temperature changes, the concentration will change as well, $y = [y(T)]_p$, in a quantitatively way difficult to know a priori and the (i) and (ii) conditions can be verified but only using a mathematical tool which uses the working combination thermodynamic equilibrium data. At this point, from the considerations emphasized so far, it becomes clear that the heat exchange analysis must start with the local (elementary) mass and heat transfer of an individual absorption process. In Fig. 2.1a, b, the two main opposite absorption processes, of absorption (resorption) and of generation (desorption), are schematically represented, respectively. Next, the word 'absorbent' is referring to a mixture of absorbent and refrigerant. In Fig. 2.1a, a mass flow, m (kg mixture), of concentration y (kg refrigerant/kg mixture) and enthalpy h (kJ/kg mixture), combines with an infinite small quantity of vapor mixture dm of concentration Y and enthalpy H , in order to result in a mixture (m, h) of higher concentration, $y + dy$. The process depicted in Fig. 2.1b is the reverse of that shown in Fig. 2.1a. The mass and heat balances of both isobar processes are written by Eqs. (2.1) and (2.2), respectively:

$$ym(y) + Y_{G(D)}dm = (y + dy)m(y + dy) \quad (2.1)$$

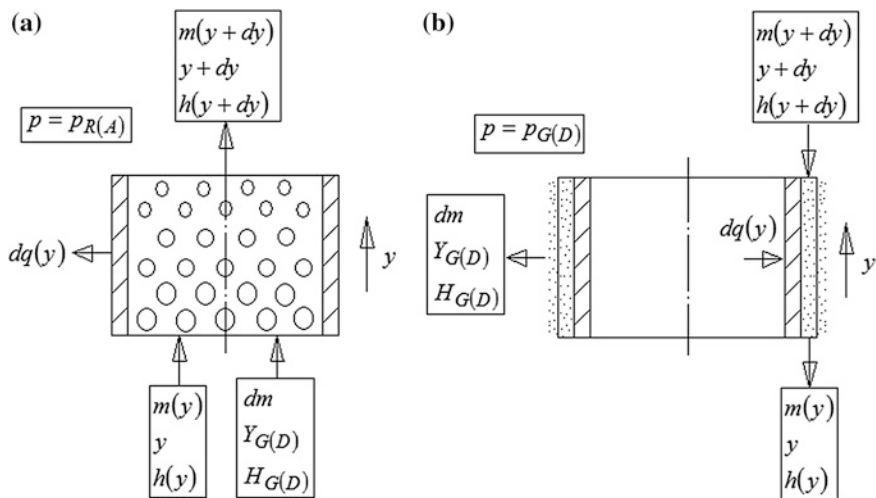


Fig. 2.1 The two opposite isobar absorption (a) and generation (b) processes, schematically representation serving to the local (elementary) mass and heat transfer analysis

$$m(y)h(y) + H_{G(D)}dm = dq + m(y+dy)h(y+dy) \quad (2.2)$$

In Eqs. (2.1) and (2.2), the lowercase and uppercase letters hold for the liquid and vapor phases, respectively, and m is the liquid phase mass flow rate. In order to avoid confusion, q will be used throughout this chapter, instead of Q , although q is an extensive property. Performing the calculation in Eq. (2.1) and neglecting the second order terms, it results:

$$\frac{dm}{m} = \frac{dy}{Y_{G(D)} - y} \quad (2.3)$$

Proceeding similarly with Eq. (2.2), we obtain:

$$dq = m \left[(H_{G(D)} - h(y)) \frac{dm}{m} - dh(y) \right] \quad (2.4)$$

Equation (2.4) can be rewritten as Eq. (2.5), taking into account Eq. (2.3) in its expression:

$$dq = m \left[\frac{H_{G(D)} - h(y)}{Y_{G(D)} - y} - \frac{\partial h(y)}{\partial y} \right] dy \quad (2.5)$$

Equation (2.5) can be put under a different form:

$$\left[\frac{\partial q}{\partial y} \right]_p = [X(y)]_p \quad (2.6)$$

which emphasizes the isobar thermal capability function, expressed by:

$$[X(y)]_p = m \left[\frac{H_{G(D)} - h(y)}{Y_{G(D)} - y} - \frac{\partial h(y)}{\partial y} \right]_p \quad (2.7)$$

The thermal capability, an extensive quantity (kJ), represents the heat exchanged during an absorption process when the absorbent suffers an elementary variation of concentration at constant pressure. This is the differential form of the known finite integral dissolution/boiling heat. The integral dissolution heat can be positive or negative, depending on the working combination nature (Niebergall 1959; Stamatescu 1972; Radcenco et al. 1983). According to the thermodynamics rule of a heat sign, in case of the common working pairs (e.g. $\text{NH}_3\text{--H}_2\text{O}$, $\text{NH}_3\text{--LiNO}_3$, $\text{NH}_3\text{--NaSCN}$, $\text{H}_2\text{O--LiBr}$), this is a negative quantity for the absorption (resorption) processes, that is these processes are exothermal (Fig. 2.1a), and is a positive quantity for the generation (desorption) processes, that is these processes are endothermal (Fig. 2.1b). The thermal capability has the same sign as that of the dissolution/boiling heat, but here we considered it a positive quantity, preferred in the practical calculus. The two terms of Eq. (2.7) bracket, given by Eqs. (2.8) and (2.9),

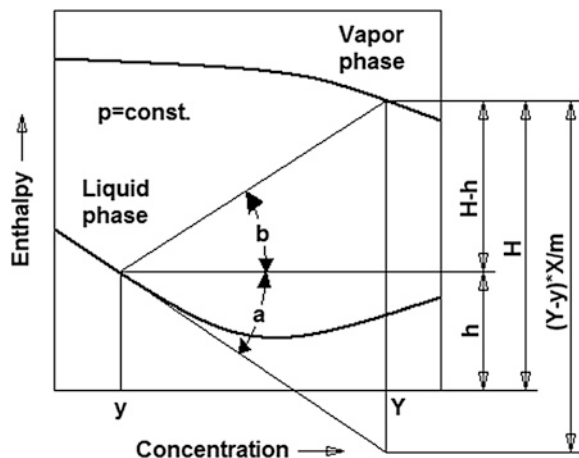
$$\tan(a) = \left[\frac{\partial h(y)}{\partial y} \right]_p \quad (2.8)$$

and

$$\tan(b) = \left[\frac{H_{G(D)} - h(y)}{Y_{G(D)} - y} \right]_p \quad (2.9)$$

can be derived graphically in an enthalpy-concentration diagram. These are shown for the $\text{NH}_3\text{--H}_2\text{O}$ in Fig. 2.2 for a certain operating point characterized by the state parameters y , Y , H , h . The simple approach presented helps finding at a glance the most recommended operating region in the solubility field of a working combination for a particular application be more effective. For instance, if the mass flow m were kept constant, a heat pump should increase the capability of its resorber in order to increase its COP. This can happen for $\text{NH}_3\text{--H}_2\text{O}$ and similar working combinations in its low concentration region, where in Eq. (2.8) the derivative is negative and both terms in Eq. (2.7) bracket are positive. However, because a generation process is the opposite of the resorption one, we expect to have in this region a high generation capability, as well. This further recommends to avoid generation processes be designed in a low concentration region of a working pair diagram. In the high concentration region, the liquid phase isobar has a positive derivative. The second term of Eq. (2.7) is therefore negative, diminishing the capability, which reason for this region is recommended for the generation processes. Similarly, extending the generation notion to the desorption ones, we expect that a high concentration region will enable to obtain lower temperatures

Fig. 2.2 Thermal capability main parameters represented in an enthalpy-concentration diagram for $\text{NH}_3\text{-H}_2\text{O}$



(e.g. negative), but with a smaller capability. Additionally, bearing in mind that a resorption process is the opposite of that of generation, we should not design a resorption based useful heating processes in a high concentration region, because here the capability and therefore the heated fluid temperature increase are reduced.

The above remarks entitle us to make a few useful higher order comments, next. In practice, not all processes of a cycle can take place simultaneously in the best region of a working pair, therefore a compromise should be made and priorities should be established: (1) The main process (that we are looking for) should be designed first in the most recommended region; (2) The rest of processes should be placed in favored regions, as much as possible, having in view, however, the second principle respect, of minimizing the exergy loss. To this extent, the cogeneration, and so much more the trigeneration, if produced by processes opposite to the main process, are increasing the exergy loss and therefore are diminishing the effectiveness with the main useful effect is produced with. This is valid for all thermodynamic cycles (e.g. a Rankine power cycle working in cogeneration of power and heat), and particularly for our coabsorbent cycles. As an example it could be mentioned the nontruncated coabsorbent cooling cycle working in cogeneration of cooling and heating, analyzed in the next chapter. Indeed, if a cogenerated heating were performed besides cooling, the cycle exergy loss increases through the useful heating output, and consequently, there will be a cooling effect reduction, as results will show. However, the cycle effectiveness of a combined energy production could be regarded from a different point of view, too. Indeed, suppose the application (society) had a synchronized need of combined energy production. In this case, the simultaneous production-consumption of two or more different forms of energy produced by a single primary heat source means a higher order application, characterized by a lower entropy value, defined as a measure of an energetic system order degree. Consequently, a cycle operating in cogeneration, or trigeneration, etc., and fulfilling the required level of output parameters, becomes of course of higher effectiveness than a higher entropy single-effect

cycle. This might be the case of some coabsorbent cycles, as it will be shown later in this book.

An algorithm based on Eq. (2.7) has been introduced in a past work by the author (Staicovici 1995). With it we evaluated a heat exchange of type (b) in the ternary working combination medium ($\text{NH}_3\text{--H}_2\text{O--LiBr}$, Radermacher and Alefeld 1982). However, this older method is less friendly in applications. For this reason, in the next section a powerful, simple, practical and easy to use method is given for the first time, perfectly integrated in a cycle thermodynamic computation algorithm, in order to assess an isobar absorption heat exchange.

2.2 The Divided Device Method for Isobar Absorption Processes Heat Exchange Assessment

The isobar thermal capability of Eq. (2.7) is a function of absorbent concentration, usually considered in the dissolution heat aspects of an individual absorption process. In a heat exchange analysis, however, it is more indicated to work with the temperature as variable, for obvious reasons. The translation from concentration to temperature results in:

$$dq(T) = [X(y(T))]_p dy(T) = \left[X(y(T)) \frac{\partial y(T)}{\partial T} \right]_p dT = [X(T)]_p dT \quad (2.10)$$

wherefrom, the new thermal capability (kJ/K), as well an extensive quantity as it depends on the involved mass, writes:

$$\left[\frac{\partial q(T)}{\partial T} \right]_p = [X(T)]_p \quad (2.11)$$

The left member first order partial derivative of Eq. (2.11) can be approximated by one of the finite difference formula, known from the numerical solving. Here it can be used for instance the forward difference (Nicolescu 1977–1980; Bakhvalov 1977):

$$\left[\frac{\partial q(T)}{\partial T} \right]_p \cong \left[\frac{q(T + \Delta T) - q(T - \Delta T)}{2\Delta T} \right]_p \quad (2.12)$$

In Eq. (2.12), the heat $q(T)$ is supposed to be a real, continuous function, defined on real intervals of temperature, $T \in [T_{DI(GI)}, T_{DO(GO)}]$ and $T \in [T_{RO(AO)}, T_{RI(AI)}]$, which the desorbition (generation) and resorbition (absorbition) processes at hand operate on, and ΔT is the temperature increment, chosen at convenience. It is enough to find $q(T)$ for the two opposite processes, desorbition and resorbition, schematically presented in Fig. 2.3a, b, respectively, in order to cover all

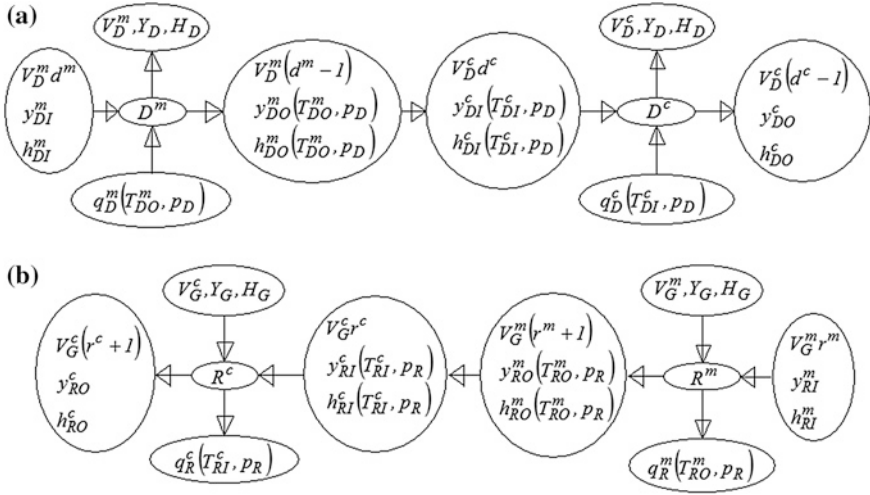


Fig. 2.3 A desorption (a) and resorption (b) processes schematic, divided in two parts, serially connected, serving for the divided device method presentation

absorption processes analysis. Each device housing an absorption process is divided in two parts, serially connected and labeled with the superscripts “m” from main and “c” from complementary, where the “Divided Device” (DD) method name comes from (Staicovici 2011). We consider first Fig. 2.3a and write the mass and heat balance for both parts. For the main part, D^m , this results in:

Mass balance:

$$V_D^m d^m y_{DI}^m = V_D^m Y_D + V_D^m (d^m - 1) y_{DO}^m \quad (2.13)$$

wherefrom, the main desorber mass flow factor is expressed by:

$$d^m = \frac{Y_D - y_{DO}^m}{y_{DI}^m - y_{DO}^m} \quad (2.14)$$

Heat balance:

$$q_D^m = V_D^m H_D + V_D^m (d^m - 1) h_{DO}^m - V_D^m d^m h_{DI}^m \quad (2.15)$$

wherefrom, the main desorber desorption heat is expressed by:

$$q_D^m = V_D^m [(H_D - h_{DO}^m) + d^m (h_{DO}^m - h_{DI}^m)] \quad (2.16)$$

Similarly, for the complementary part, D^c , this results in:

Mass balance:

$$d^c = \frac{Y_D - y_{DO}^c}{y_{DI}^c - y_{DO}^c} \quad (2.17)$$

Heat balance:

$$q_D^c = V_D^c [(H_D - h_{DO}^c) + d^c (h_{DO}^c - h_{DI}^c)] \quad (2.18)$$

The above equations have two unknowns, V_D^m and V_D^c . These can be found with the help of the following equations:

Vapor mass balance on desorber and its constitutive parts:

$$V_D^m + V_D^c = V_D \quad (2.19)$$

Mass flow continuity between main and complementary parts:

$$V_D^m (d^m - 1) = V_D^c d^c \quad (2.20)$$

State parameters continuity between main and complementary parts:

$$T_{DO}^m = T_{DI}^c = T \quad (2.21)$$

$$p_{DO}^m = p_{DI}^c = p_D \quad (2.22)$$

The heat $q(T)$ is calculated in a point of temperature T always situated to the boundary between the two m and c parts of a device, as Eqs. (2.21) and (2.31) show. From Eqs. (2.19) and (2.20), it results:

$$V_D^m = V_D \frac{d^c}{d^c + d^m - 1} \quad (2.23)$$

and

$$V_D^c = V_D \frac{d^m - 1}{d^c + d^m - 1} \quad (2.24)$$

Equations (2.13)–(2.24) hold true for a generation device also, provided that the index D be changed by G and the mass flow factor d be changed by g . We consider now Fig. 2.3b. Proceeding similarly, the items given below hold true in case of a resorption process. For the main part, R^m , we obtain:

Mass balance:

$$r^m = \frac{Y_G - y_{RO}^m}{y_{RO}^m - y_{RI}^m} \quad (2.25)$$

Heat balance:

$$q_R^m = V_G^m [(H_G - h_{RO}^m) + r^m (h_{RI}^m - h_{RO}^m)] \quad (2.26)$$

For the complementary part, R^c , it results:

Mass balance:

$$r^c = \frac{Y_G - y_{RO}^c}{y_{RO}^c - y_{RI}^c} \quad (2.27)$$

Heat balance:

$$q_R^c = V_G^c [(H_G - h_{RO}^c) + r^c (h_{RI}^c - h_{RO}^c)] \quad (2.28)$$

The two unknowns, V_G^m and V_G^c can be found with the help of the following equations:

$$V_G^m + V_G^c = V_G \quad (2.29)$$

$$V_G^m (r^m + 1) = V_G^c r^c \quad (2.30)$$

$$T_{RO}^m = T_{RI}^c = T \quad (2.31)$$

$$p_{RO}^m = p_{RI}^c = p_R \quad (2.32)$$

From Eqs. (2.29) and (2.30), the complementary vapor results this time:

$$V_G^m = V_G \frac{r^c}{r^c + r^m + 1} \quad (2.33)$$

and

$$V_G^c = V_G \frac{r^m + 1}{r^c + r^m + 1} \quad (2.34)$$

Equations (2.25)–(2.34) hold true for an absorption device also, provided that the index G and R be changed by D and A , respectively, and the mass flow factor r be changed by a . The thermal capability of an absorption processes is found within the limits of the DD method considering Eq. (2.12) for the appropriate heat $q(T)$ expressed by one of Eqs. (2.15, 2.18, 2.26, 2.28), etc. in a consistent way for all temperature T values which cover the entire process operation. Additionally, we stress that it is not important which part of a device heat expression is used in Eq. (2.12), the result is the same whether for instance we use the q_D^m or q_D^c heat for the desorber. This equal choice results from equaling Eq. (2.12) numerator of both parts:

$$q_i^m(T + \Delta T) - q_i^m(T - \Delta T) = q_i^c(T - \Delta T) - q_i^c(T + \Delta T), \quad i = D, R, G, A \quad (2.35)$$

Rearranging the terms, it results the true result for all T , if we beared in mind equations of type (2.21) or (2.31):

$$q_i^m(T + \Delta T) + q_i^c(T + \Delta T) = q_i^m(T - \Delta T) + q_i^c(T - \Delta T) = q_i = \text{const.} \quad (2.36)$$

Further on, the heat expression utilized in Eq. (2.12) was that corresponding to the main part. The main part of a device was considered computationally that part which allows the absorbent access into the device. Proceeding in this way it enables the thermodynamic state of absorbent going into device be taken into account, which obviously is crucial for a correct absorbtion process heat exchange analysis.

The method, completed by details of application, is covered once for the analysis of the type (a) heat exchange, with a single absorption process, and twice in a correlated way for the type (b) heat exchange. The DD method analysis results will be shown in the next chapters wherever it will be necessary.

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