

5 IZBOR

V tem koraku izbiramo med najboljšimi idejami za nadaljnji razvoj produkta. Ideje za produkt primerjamo na osnovi kemijskih in inženirskih kriterijev ter na osnovi drugih manj eksaktnih kriterijev, kot sta "udobje" in "varnost".

Pri primerjavi produktov na osnovi kemijskih in inženirskih kriterijev uporabljamo znanja iz: termodinamike, kinetike, prenosa toplote in snovi, fluidne mehanike... Naredimo vsaj približne izračune, ki so potrebni za izbor produkta.

Primerjava produktov na osnovi manj eksaktnih kriterijev je bolj kompleksna. Manj eksaktni kriteriji vključujejo odziv uporabnikov in javno mnenje, ki se lahko spreminjajo s časom in so različni za različna tržišča.

Težja je primerjava produktov, ki se med seboj zelo razlikujejo.

Pri izboru je potrebno upoštevati dejavnike tveganja za neuspeh.

Pristop k izbiranju je podoben kot pri pregledu idej (poglavje 4.4). Uporabljamo izbirno matriko: Določimo pomembne kriterije. Posameznim kriterijem pripišemo pomembnost z utežnimi faktorji. Ideje ocenimo. Ocenjujemo tudi referenčni produkt. Izberemo idejo z najvišjim številom točk.

V fazi izbora končne ideje je potrebno upoštevati vse detajle. Preprečiti je potrebno napačne ocene. Kriteriji morajo biti brezhibno razdelani, utežni faktorji čim bolj pravilni. Analiza občutljivosti utežnih faktorjev je nujna. Potrebno je poiskati še drugo mnenje. Dodatna raziskava trga je zelo zaželena.

Na koncu koraka izbor moramo izbrati nov produkt. Naslednji korak je načrtovanje postopka za izdelavo produkta.

5.1 IZBOR NA OSNOVI TERMODINAMIKE

Ko modificiramo obstoječ produkt pogosto izbiramo na osnovi termodinamike.

Materiale v produktu zamenjujemo z namenom izboljšati funkcionalnost produkta ("performance") ali pa z namenom ohraniti funkcionalnost, ko želimo uporabiti druge materiale, da znižamo ceno produkta, povečamo varnost produkta...

Zamenjava materialov (surovin)

Tipičen primer zamenjave materiala je zamenjava topila v organskem produktu z manj hlapnim, manj toksičnim in cenejšim topilom. Metilen klorid (CH_2Cl_2 , ki je zelo uporabno topilo v proizvodnji kemikalij) je kancerogen. Aceton (CH_3COCH_3 , ki ga zelo pogosto uporabljamo v kemijskem laboratoriju) je bolj toksičen od metanola (CH_3OH).

Ko iščemo zamenjavo za topilo, je najbolje, da to počnemo na osnovi laboratorijskega eksperimentalnega dela. Ker pa je zelo pomembno, da smo pri tem predvsem hitri in učinkoviti, si pomagamo s topnostnimi parametri (δ). Za topnost mora biti izpolnjen pogoj: $(\delta_{\text{topilo}} - \delta_{\text{topljenec}})^2 = 0$. Pomeni, da iščemo novo topilo med topili, ki majo podoben topnostni parameter kot topilo, ki ga zamenjujemo. Glej tabelo (Table 4.1-1). Na primer kloroform bomo poskušali zamenjati z benzenom.

Tabela topnostnih parametrov (Vir: E. L. Cussler in G. D. Moggridge, *Chemical Product Design*, Cambridge University Press, Cambridge, 2001.)

TABLE 4.1-1 Solubility Parameters			
Formula	Substance	V (cm ³ /mol)	δ (cal ^{1/2} cm ^{-3/2})
Halogenated solvents			
C ₆ F ₁₄	perfluoro- <i>n</i> -hexane	205	5.9
C ₇ F ₁₆	perfluoro- <i>n</i> -heptane	226	6.0
C ₆ F ₁₂	perfluorocyclohexane	170	6.1
(C ₄ F ₉) ₃ N	perfluoro tributylamine	360	5.9
C ₂ Cl ₃ F ₃	1,1,2-trichloro,1,2,2-trifluoroethane	120	7.1
CH ₂ Cl ₂	methylene chloride	64	9.8
CHCl ₃	chloroform	81	9.2
CCl ₄	carbon tetrachloride	97	8.6
CHBr ₃	bromoform	88	10.5
CH ₃ I	methyl iodide	63	9.9
CH ₂ I ₂	methylene iodide	81	11.8
C ₂ H ₅ Cl	ethyl chloride	74	8.3
C ₂ H ₅ Br	ethyl bromide	75	8.9
C ₂ H ₅ I	ethyl iodide	81	9.4
C ₂ H ₄ Cl ₂	1,2 dichloroethane (ethylene chloride)	79	9.9
C ₂ H ₄ Cl ₂	1,1 dichloroethane (ethyldene chloride)	85	9.1
C ₂ H ₄ Br ₂	1,2 dibromoethane	90	10.2
C ₂ H ₃ Cl ₃	1,1,1 trichloroethane	100	8.5
Aliphatic hydrocarbons			
C ₅ H ₁₂	<i>n</i> -pentane	116	7.1
	2-methyl-butane (isopentane)	117	6.8
	2,2-dimethyl propane (neopentane)	122	6.2
C ₇ H ₁₄	<i>n</i> -hexane	132	7.3
C ₇ H ₁₆	<i>n</i> -heptane	148	7.4
C ₈ H ₁₈	<i>n</i> -octane	164	7.5
	2,2,4-trimethylpentane	166	6.9
C ₁₆ H ₃₄	<i>n</i> -hexadecane	294	8.0
C ₆ H ₁₂	cylohexane	109	8.2
C ₇ H ₁₄	methylcyclohexane	128	7.8
C ₆ H ₁₂	1-hexene	126	7.3
C ₈ H ₁₆	1-octene	158	7.6
C ₆ H ₁₀	1,5-hexadiene	118	7.7
Aromatic hydrocarbons			
C ₆ H ₆	benzene	89	9.2
C ₇ H ₈	toluene	107	8.9
C ₈ H ₁₀	ethylbenzene	123	9.9
	<i>o</i> -xylene	121	9.0
	<i>m</i> -xylene	123	8.8
	<i>p</i> -xylene	124	8.8
C ₈ H ₈	styrene	116	9.3
C ₁₀ H ₈	naphthalene	123	9.9
Inorganics			
Br ₂	bromine	51	11.5
I ₂	iodine	59	14.1
S ₈	sulfur	135	12.4
P ₄	phosphorus	70	13.1
CCl ₄	carbon tetrachloride	97	8.6
SiCl ₄	silicon tetrachloride	115	7.6
SnCl ₄	stannic chloride	118	8.7
WF ₆	tungsten hexafluoride	88	8.0
Si(CH ₃) ₄	silicon tetramethyl	136	6.2

List reproduced from Hildebrand, Prausnitz, and Scott.

Zamenjava materialov v produktih, ko ne želimo vplivati na delovanje produkta

Ko zamenjujemo material v produktih (za potrošnike, za široko potrošnjo) in želimo, da zamenjava materiala ne vpliva na funkcionalnost produkta, moramo biti pozorni na dve stvari:

- Zamenjava naravne kemikalije s sintetično in obratno: Če imata kemikaliji popolnoma enako kemijsko strukturo, zamenjava iz vidika učinkovitosti oziroma delovanja produkta ne bo vprašljiva. Do odstopanj prihaja le takrat, ko kemikalije niso čiste. Največkrat je manj čista naravna kemikalija. Včasih pa je to lahko tudi prednost (Na primer naravna surovina vsebuje tudi naravne emulgatorje, ki omogočajo lažje mešanje naravne surovine z drugimi surovinami v formuliranem produktu.). Dejstvo pa je, da lahko produkt pod oznako "Naravno" prodamo po višji ceni.

- Vedeti moramo, kdaj in zakaj zamenjava materiala vpliva na lastnosti produkta, ki so ključne za uporabnike (Na primer: "gostota", "gladkost" in "mazavost" kreme.). Če poznamo zvezo med sestavo, strukturo, kazalci učinkovitosti (kvantitativni parametri za kakovost produkta) in faktorji kakovosti (opisnimi lastnostmi produkta, ki jih podajajo potrošniki), večjih težav pri zamenjavi ne bi smeli imeti. Če temu ni tako, zamenjujemo material empirično (s poskušanjem).

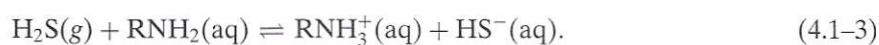
Zamenjava materialov v produktih z namenom izboljšati delovanje produkta

Pogosto z zamenjavo materialov želimo izboljšati delovanje, učinkovitost oziroma funkcionalnost ("performance") produkta. Neredko so lastnosti materialov (surovin) in posledično tudi delovanje produkta močno odvisni od temperature in/ali pH vrednosti.

Odličen primer so vodotopni absorbenti, kot je monoetanol amin, za absorpcijo kislih plinov, kot je ogljikov dioksid, iz plinske v tekočo (vodno) fazo. Amin hitro reagira z ogljikovim dioksidom. V reakciji nastane v vodi topen karbonat. Nato se raztopina monoetanol amina regenerira s segrevanjem, ker pri povišani temperaturi karbonat razpada. Zaradi vedno višjih cen energije si želimo, da bi bila reakcija amina s plinom hitra in da bi bila njena konstanta ravnotežja močno odvisna od temperature.

Primer: Absorpcija H₂S (Vir: E. L. Cussler in G. D. Moggridge, Chemical Product Design, Cambridge University Press, Cambridge, 2001.)

To seek such amines, we again return to simple thermodynamic ideas. To focus these ideas, we consider the reaction



Thus,

$$[\text{RNH}_3^+][\text{HS}^-] = K[\text{RNH}_2][\text{H}_2\text{S}], \quad (4.1-4)$$

where the quantities in square brackets are concentrations and K is the equilibrium constant for this reaction.

We want K to vary strongly with temperature. To seek this variation, we remember that

$$K = e^{-\Delta G/RT} = e^{-\Delta H/RT + \Delta S/R}, \quad (4.1-5)$$

where ΔG , ΔH , and ΔS are the free energy, enthalpy, and entropy changes of this reaction. Thus, we seek amines that show large enthalpies of reaction when combined with H₂S.

Primer: Ekstrakcija tekoče-tekoče (Vir: E. L. Cussler in G. D. Moggridge, Chemical Product Design, Cambridge University Press, Cambridge, 2001.)

As a case illustrating variation of a property with pH, we consider drug purification. Many drugs have either carboxylic acid ($-\text{COOH}$) or amine ($-\text{NH}_2$) groups that can be used to facilitate their purification by liquid-liquid extraction. As an example, we imagine an antibiotic like penicillin, which is a carboxylic acid. We expect that at equilibrium, the concentrations in an organic solvent and in water are at equilibrium:

$$\begin{aligned} [\text{drug in organic}] &= K[\text{drug in water}], \\ [\text{RCOOH}]_{\text{org}} &= K[\overline{\text{RCOOH}}]_{\text{H}_2\text{O}}, \end{aligned} \quad (4.1-6)$$

where K is again an equilibrium constant. The drug in organic solution will normally be protonated, and hence in only one form. However, the drug in aqueous solution may either be protonated or ionized.

The ionization of the drug in aqueous solution means that the equilibrium constant K can be a strong function of pH. To see why, we first note that the concentration $\overline{\text{RCOOH}}$ actually includes different forms:

$$[\overline{\text{RCOOH}}]_{\text{H}_2\text{O}} = [\text{RCOOH}]_{\text{H}_2\text{O}} + [\text{RCOO}^-]_{\text{H}_2\text{O}}. \quad (4.1-7)$$

These forms are in equilibrium:

$$[\text{H}^+]_{\text{H}_2\text{O}}[\text{RCOO}^-]_{\text{H}_2\text{O}} = K_a[\text{RCOOH}]_{\text{H}_2\text{O}} \quad (4.1-8)$$

where K_a is the dissociation constant for this acidic drug. The true thermodynamic equilibrium across the organic-water interface is not that in Equation 4.1-6, but

$$[\text{RCOOH}]_{\text{org}} = K'[\text{RCOOH}]_{\text{H}_2\text{O}}. \quad (4.1-9)$$

Combining Equations 4.1-7 to 4.1-9, we find that

$$[\text{RCOOH}]_{\text{org}} = \left(\frac{K'[\text{H}^+]_{\text{H}_2\text{O}}}{K_a + [\text{H}^+]_{\text{H}_2\text{O}}} \right) [\overline{\text{RCOOH}}]_{\text{H}_2\text{O}}. \quad (4.1-10)$$

Thus

$$K = \frac{K'[\text{H}^+]_{\text{H}_2\text{O}}}{K_a + [\text{H}^+]_{\text{H}_2\text{O}}}. \quad (4.1-11)$$

The apparent equilibrium constant K in Equation 4.1-6 varies dramatically with acid concentration. This variation, explored further in an example below, is useful in drug purification by extraction.

Primeri (Vir: E. L. Cussler in G. D. Moggridge, Chemical Product Design, Cambridge University Press, Cambridge, 2001.)

EXAMPLE 4.1-1 A BETTER SKIN LOTION

Our employer currently manufactures a variety of skin care products. Market research shows a need for a “thinner,” “creamier” skin lotion. Our idea is to develop such a lotion that is twice as “thin” (i.e., half as “thick”) but also twice as “creamy.” How should we seek new ingredients?

SOLUTION

To make the lotion half as thick, we can simply reduce its viscosity. If the lotion is Newtonian, we should reduce its viscosity four times. However, to double the lotion's "creaminess," we must increase its "smoothness" four times, because past experiments show that

$$\text{"creaminess"} = [(\text{"thickness"}) \times (\text{"smoothness"})]^{1/2}$$

This increased "smoothness" requires decreasing the coefficient of friction by eight times. This may be hard to do.

EXAMPLE 4.1-2 A POLLUTION PREVENTING INK

For the purposes of this example, a lithographic ink can be idealized as containing only four components: a pigment, an oil, a resin, and a solvent. The pigment, frequently colloidal carbon, is important to the ink, but not a key in pollution. The oil, a mixture of natural products such as castor and linseed oils, typically contains fatty acids with multiple double bonds, such as linoleic acid and linolenic acid. These double bonds crosslink in the presence of oxygen, making the ink permanent. The resin is a low molecular weight, highly polydisperse condensation polymer, made for this purpose. The solvent, frequently methylene chloride (CH_2Cl_2), is used to adjust the ink's rheology to give good printing.

We want to replace methylene chloride with a less dangerous solvent. What should we choose?

SOLUTION

We must seek solvents whose solubility parameters are close to that of methylene chloride. From Table 4.1-1, we find that the solubility parameter of methylene chloride is $9.8 (\text{cal}/\text{cm}^3)^{1/2}$. We then look for inexpensive solvents with similar solubility parameters. Benzene, toluene, and naphthalene are three possible choices. All are carcinogens, though felt to be less dangerous than methylene chloride. Benzene is excessively volatile, and naphthalene is solid at the temperatures normally used for printing. Thus we choose toluene as a substitute for methylene chloride and start experiments. This is a conservative choice: the toluene is still toxic and will generate emissions, but the modified ink should work well.

EXAMPLE 4.1-3 ANTIBIOTIC PURIFICATION

We are trying to modify an existing purification to use with a new acid antibiotic whose pK_a is 4.52. We want to alter the pH and hence alter the distribution of the antibiotic between water and butyl acetate. What pH range should we use?

SOLUTION

To begin, we should return to the definition of the pK_a , which is

$$pK_a = -\log_{10} K_a = \log_{10} \frac{[\text{H}^+]_{\text{H}_2\text{O}}[\text{RCOO}^-]_{\text{H}_2\text{O}}}{[\text{RCOOH}]_{\text{H}_2\text{O}}},$$

where the various concentrations are defined by Equation 4.1–8. The definition of the pH is

$$\text{pH} = -\log_{10}[\text{H}^+].$$

Thus from Equation 4.1–11, we see

$$\frac{K}{K'} = \frac{1}{1 + 10^{\text{pH} - \text{p}K_a}}.$$

When the pH is much less than 4.52, K approaches K' . When the pH is much greater than 4.52, K becomes small. By adjusting the pH, we can change K and purify the drug.

5.2 IZBOR NA OSNOVI KINETIKE

Termodinamika nam daje odgovor na vprašanje "Ali je mogoče?". Kinetika nam daje odgovor na vprašanje "Kako hitro?". Pri kemijskih produktih navadno obravnavamo: hitrost kemijske reakcije, hitrost prenosa snovi in hitrost prenosa toplote.

Kemijska kinetika

Za oceno hitrosti kemijskih reakcij moramo poznati reakcijski mehanizem in konstante reakcijske hitrosti. Ker konstant reakcijskih hitrosti ne moremo oceniti (ne da bi tvegali, da naredimo večjo napako) je eksperimentalno delo neizogibno.

Za reakcijo prvega reda je hitrost kemijske reakcije (r [mol/(l · s)]):

$$r = k \cdot c$$

kjer sta k konstanta reakcijske hitrosti v s^{-1} in c koncentracija reaktanta v mol/l. Za reakcijo drugega reda je hitrost kemijske reakcije:

$$r = k \cdot c_1 \cdot c_2$$

kjer so k konstanta reakcijske hitrosti v $1/(\text{mol} \cdot \text{s})$, c_1 koncentracija reaktanta 1 v mol/l in c_2 koncentracija reaktanta 2 v mol/l. Ko je reaktant 2 v tako velikem prebitku, da se njegova koncentracija med reakcijo le malo spreminja (c_2 je skoraj konstantna), govorimo o reakciji psevdoprvega reda. To je eden izmed možnih vzrokov, zakaj je navidezni red reakcije, v kateri sodelujeta dva reaktanta, lahko 1. Za reakcije ničtega reda je hitrost reakcije:

$$r = k$$

kjer je k konstanta reakcijske hitrosti v mol/(l · s). Reakcije ničtega reda so značilne za katalitske reakcije.

S pomočjo eksperimentalnih podatkov lahko dobimo vrednosti k (ki so odvisne od temperature!). Ob znanih maksimalnih koncentracijah reagentov lahko izračunamo maksimalne hitrosti kemijske reakcije.

Ko so kemijski koraki v reakciji hitri, postane hitrost kemijske reakcije kontrolirana s prenosom snovi. Snovna prestopnost (ali koeficient snovnega prenosa) pa se lahko dokaj dobro oceni.

Če ocenimo, da je maksimalna hitrost reakcije specifičnega procesa (ki je kontroliran s kemijsko reakcijo in/ali prenosom snovi) nižja od tiste, ki jo potrebujemo, tega procesa za nov produkt ne bomo izbrali.

Za heterogene sisteme lažje napovemo maksimalne hitrosti kot za homogene sisteme.

- ❖ Primer: Napoved maksimalne hitrosti za heterogeno reakcijo – zgorevanje trdnega delca v zraku. Reakcije je 1. reda in je ireverzibilna. Navidezna konstanta reakcijske hitrosti (k) je:

$$\frac{1}{k} = \frac{1}{k_D a} + \frac{1}{k_{površina}}$$

kjer je k_D snovna prestopnost, a je površina delca na volumen in $k_{površina}$ kinetična hitrostna konstanta kemijske reakcije na površini delca. Če je hitrost kemijske reakcije na površini visoka, je $k_{površina}$ velik in bo proces kontroliran s prenosom snovi. Prenos snovi lahko ocenimo s predpostavko, da je k_D reda velikosti 10^{-3} cm/s v tekočini in 1 cm/s v plinu. Hitrostno konstanto k poznamo, če poznamo a .

Številne reakcije v prisotnosti mikroorganizmov, delcev katalizatorja ali kapljic v emulziji imajo enake značilnosti.

Obstajajo tudi različne korelacije za prenos snovi v takšnih sistemih.

- ❖ Primer: Napoved maksimalne hitrosti za homogeno reakcijo. Reakcija je trenutna (izredno hitra) in ireverzibilna. Če je sistem pred reakcijo idealno premešan, velja:

$$k = 4\pi(D_1 + D_2)\sigma N_A c_2$$

kjer sta D_1 in D_2 difuzivnosti limitnega reaktanta in reaktanta v prebitku, σ je kolizijski premer (recimo 0,5 nm), N_A je Avogadrovo število in c_2 je koncentracija reagenta v prebitku. Na žalost enačba za sisteme s trenutno reakcijo ne velja, saj takšni sistemi ne morejo biti idealno premešani pred začetkom reakcije.

Pri večini hitrih homogenih reakcij hitrost omejuje mešanje. V splošnem, je hitrostna konstanta za mešanje:

$$k = \left[\frac{4(D_1 + D_2)}{l^2} \right]$$

kjer je l povprečna velikost vrtinca pri mešanju. V hitro mešanih tekočinah sta l okoli 30 μm in D okoli 10^{-5} cm²/s. Pomeni, da je k okoli 10^4 s⁻¹.

Če je le mogoče (kar ni vedno), oceno potrdimo še z eksperimentom.

Snovna in toplotna prestopnost

Ker sta prenos toplote in snovi fizikalna procesa (ni kemijske spremembe snovi), se snovne in toplotne prestopnosti (koeficienti snovnega in toplotnega prenosa) v istem agregatnem stanju za različne snovi le malo razlikujejo med seboj. Zato obširno eksperimentalno delo za določanje toplotne in snovne

prestopnosti ni vedno nujno potrebno. Če ocenimo toplotne in snovne prestopnosti, lahko ocenimo hitrosti prenosa toplote in snovi.

Snovna prestopnost (k) za tekočine je reda velikosti 10^{-3} cm/s, difuzivnost (D) pa je reda velikosti 10^{-5} cm²/s.

S pomočjo filmske teorije oziroma teorije mejnega sloja ($k = D / \delta$) lahko ocenimo debelino filma tekočine (δ), po kateri se koncentracija snovi spreminja, in je okoli 0,01 cm.

Snovna prestopnost (k) za pline je reda velikosti 1 cm/s, difuzivnost (D) pa je reda velikosti 0,1 cm²/s. Po filmski teoriji je debelina mejnega sloja okoli 0,1 cm.

Toplotna prestopnost (h) za pline je reda velikosti 1 W/(m² · K), termična difuzivnost (α) pa je reda velikosti 0,1 cm²/s.

Toplotna prestopnost (h) za tekočine je reda velikosti 1 kW/(m² · K), termična difuzivnost (α) pa je reda velikosti 10^{-5} cm²/s.

Tabela: Grobe ocene toplotne in snovne prestopnosti (Vir: E. L. Cussler in G. D. Moggridge, Chemical Product Design, Cambridge University Press, Cambridge, 2001.)

Situation	k (cm/sec)	$h / \rho \hat{C}_p$ (cm/sec)	h (W/m²°K)
Flowing gases	1	1	3
Flowing water	0.001	0.1	5000
Flowing organics	0.001	0.1	1000
Condensing steam or boiling water	—	—	2000

Note: The values given are useful only in the order of magnitude estimates made during product selection. More accurate values should be used when planning manufacture.

Primeri (Vir: E. L. Cussler in G. D. Moggridge, Chemical Product Design, Cambridge University Press, Cambridge, 2001.)

EXAMPLE 4.2-1 A DEVICE THAT ALLOWS WINES TO BREATHE

David Anderson, an alumnus of the University of Minnesota who says he got poor grades in chemistry, is the buyer for the best wine store in Minneapolis-St. Paul. In an interview, he described the practice of allowing wines – especially red wines – to “breathe” by exposing them to air before drinking. The following is a summary of his ideas on this subject.

Wines need to breathe to reduce the “hard” and “soft” tannins that naturally occur. These are reduced by exposing the wine to oxygen. Reactions of oxygen with polyphenols may also be involved. Such exposure enhances flavor, allowing both fruit taste and aroma to be more clearly perceived.

The amounts of oxygen required by wines vary widely. Uncorking the bottle for 15 minutes before drinking is useless, but exposing wines to excessive oxygen over time will turn them into vinegar. Mr. Anderson suggests one good way is to pour the wine from the bottle into a decanter, leaving any residue behind. Several pours between decanters is better. Mr. Anderson even has one friend who pours the wine into a larger glass, covers the glass with his hand, and gives the wine a good shake.

In thinking about this, we must remember that wine is unstable, and can be destroyed by mistreatment. Heat and excessive oxygen are major enemies. Corks often fail, so that different bottles from the same vineyard and the same vintage may be different. Because of this, Mr. Anderson applauds the use of plastic corks. Moreover, like humans, wines can become fragile with age: a fine 25-year-old Bordeaux can degrade while it sits in the glass.

Estimate the aeration needed in a product that can let wine breathe in only a few minutes.

SOLUTION

A problem like this begs for experimentation. Our experiment used four wines:

Montepulciano, *CITRA*, Italy (1996) \$6/1500 ml
Cabernet Sauvignon, *Castillero de Diablo*, Chile, (1996) \$8/750 ml
Gamay, *Chateau la Charge*, France (1995) \$12/750 ml
Zinfandel, *Folie a Deux*, USA (1997) \$18/750 ml

Aeration can make a startling difference, especially for cheap, freshly opened wine. We tried four methods:

1. Open the bottle for 15 minutes.
2. Decant into an open pitcher and let the wine sit 2 hours.
3. Decant the wine fast three times, entraining air.
4. Shake for 10 seconds in a large glass.

Then we tested the wine.

The first method is useless, as David Anderson suggested. The other three give roughly similar taste improvements. Still another method, putting wine in a blender, aerates it excessively, dramatically reducing flavor.

These results are consistent with estimates based on mass transfer. To see why, we make a mass balance on oxygen transferred into the wine:

$$\frac{\text{oxygen transferred, } M}{\text{wine volume, } V} = \{[\text{mass transfer coefficient, } k][\text{partition coefficient, } H] \times [\text{concentration in air, } c_1]\} \times [\text{area per volume, } a][\text{time, } t].$$

In symbolic terms,

$$m/V = \{kHc_1\}At,$$

$$\frac{m/V}{Hc_1} = kAt = NTU,$$

where NTU is the number of transfer units. NTU is a dimensionless quantity, commonly used in the design of absorption towers.

Estimates for our four experimental methods are summarized in Table 4.2–2. The mass transfer coefficients in this table were estimated in different ways. For the first two methods we assumed a value of 10^{-3} cm/sec, as suggested in Table 4.2–1. The aeration achieved by the third method was estimated by using correlations for bubbles and for the fourth from the penetration theory of mass transfer. These

TABLE 4.2–2 Four Methods for Letting Red Wine Breathe

Method	Mass Transfer Coefficient (cm/sec)	Wine Area/Volume (cm ² /cm ³)	Time (sec)	NTU
Uncork bottle for 15 minutes	10^{-3a}	3/750	900	0.004
Decant into pitcher 2 hours before serving	10^{-3a}	100/750	7200	1
Decant three times, entraining 0 (5 cm ³) air	20×10^{-3b}	0.4 ^b	120	0.5
Shake 30 cm ³ of wine twenty times in a 300-cm ² glass	7×10^{-3c}	300/30	10 ^c	0.7

^a This typical value can be estimated from Table 4.2–1 or from the free convection caused by ethanol evaporation.

^b Estimated from observed 5 cm³ of 0.1-cm bubbles entrained in each decantation.

^c Estimated from penetration theory with a penetration time of one shake (0.5 s).

methods were preferred because of the small bubbles and short contact times, which give unusually large mass transfer.

The estimates in Table 4.2–2 are reassuringly consistent. Opening the bottle for 15 minutes gives less than 0.01 transfer units: it does not give enough oxygen transfer. The other three methods give around one transfer unit, apparently enough to aerate the wine, but not so much as to cause a lot of flavor loss. These three methods supply close to one transfer unit even though they have radically different areas, times, and mass transfer coefficients.

Thus our selected design – whatever it is – should give around one transfer unit. Any engineering solution meeting this specification will give about the same performance. However, we believe that the success of a “wine breather” will depend strongly on the aesthetics of the aerator’s design. It is our own confidence in our lack of ability in this aesthetic area that inhibits us in developing this product.

EXAMPLE 4.2-2 A PERFECT COFFEE CUP

We have been asked by a chain of upmarket coffee shops to develop an improved coffee cup. The current cup has a volume of about 200 cm^3 and a total surface area, including the top and bottom, of 200 cm^2 . The improved cup should keep the coffee at an optimal “drinkable” temperature, estimated to be 51°C , for as long as possible. Data for coffee cooling in the current covered and uncovered cups are shown in Figure 4.2-1.

Generating ideas has led to three major directions for an improved cup:

1. A better insulated cup;
2. A cup with its own, self-contained heater; and
3. A cup with a thermal reservoir that melts around 50°C .

Select among these ideas to see which merits further development.

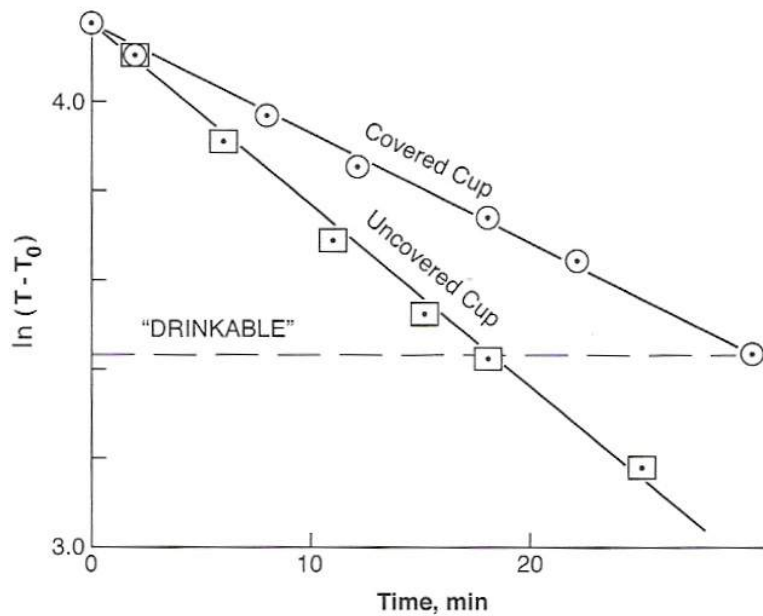


Figure 4.2-1. Cooling a Coffee Cup. The slope of the data on this semilogarithmic plot is a measure of the overall heat transfer coefficient of the cup. In these experiments, the ambient temperature was 20°C .

SOLUTION

We begin by trying to explain the data in Figure 4.2–1. From an unsteady energy balance on the coffee, we find

$$\frac{d}{dt}[\rho \hat{C}_v V T] = UA(T_0 - T),$$

where ρ is the coffee's density; $\hat{C}_v (\doteq \hat{C}_p)$ is its specific heat capacity; V is its volume; t is the time; U is the overall heat transfer coefficient averaged over the coffee; A is the coffee's surface area, including the contact with the cup and with the air; and T and T_0 are the temperatures of the coffee and the surrounding air, respectively. This equation is easily integrated to give

$$\frac{T - T_0}{T(t=0) - T_0} = e^{-t/\tau},$$

where the characteristic time τ is

$$\tau = \frac{\rho \hat{C}_v V}{UA}.$$

This equation implies that the temperature of the cooling coffee should vary exponentially with time, which is consistent with the experiments shown in the figure.

Note that the slope of the data shown is a measure of τ and hence of the overall heat transfer coefficient. In particular, for the uncovered cup,

$$\begin{aligned} \tau &= 24 \text{ min}, \\ \frac{\rho \hat{C}_v V}{UA} &= \frac{(10^3 \text{ kg/m}^3)[(1.18 \times 10^3 \text{ J)/(kg }^\circ\text{K)}] 2 \times 10^{-4} \text{ m}^3}{U(0.02 \text{ m}^2)(60 \text{ s/min)}}, \\ U &= 57 \text{ W/m}^2 \text{ }^\circ\text{K}. \end{aligned}$$

For the covered cup, τ is 40 min and U is 17 W/m² °K. In this example, we have some experimental data available, and so estimates for heat transfer coefficients are not required.

We are now in a position to select among the three ideas suggested above. We first consider the idea of a better insulated cup. This idea aims at decreasing U , and hence reducing the slope of the data in Figure 4.2–1. Note that the coffee does not stay at the drinkable temperature, but rather passes that temperature more slowly. Still, there are many routes to this improved insulation, some of which are cheap. This simple, powerful idea merits further development.

The second idea, a cup with its own heater, is weaker. In this idea, we could let the coffee cool uncovered until 50°C, and then let the heater take over. From our data, we see that the heater must provide power of about

$$\begin{aligned} Q &= UA(T - T_0), \\ &= \frac{57 \text{ W}}{\text{m}^2 \text{ }^\circ\text{K}}(0.04 \text{ m}^2)(51 - 20^\circ\text{C}), \\ &= 70 \text{ W}. \end{aligned}$$

An average c-cell battery provides about 1 W, so we will need a lot of batteries for this concept. It just does not make sense.

The third idea is to build a coffee cup with a thermal reservoir. The physical form of this reservoir is not clear at this stage; it might replace the insulation with a layer of a substance that melts near 50°C. A coffee cup with such a thermal reservoir would behave very differently to normal cups. When the hot coffee is added, the reservoir substance would melt, cooling the coffee. When the coffee has cooled to the compound's melting temperature, the compound would begin to freeze. The heat of fusion would keep the coffee near the melting temperature until all the compound was frozen. The coffee would then cool in the normal way.

Although this could potentially work, we need more information about possible substances to make an informed judgment. One group of substances are higher hydrocarbon waxes, such as pentacosane (C₂₅H₅₂) which melts at 53°C with a heat of fusion ($\Delta \hat{H}_f$) of 220 kJ/kg, or beeswax, which melts at about the same temperature with a heat fusion around 180 kJ/kg. We can find the mass m of the substance required to keep the coffee at the melting temperature for a time t from the relation

$$m\Delta \hat{H}_{\text{fusion}} = Qt = UA(T - T_0)t.$$

For example, for beeswax, we can keep the coffee at 53°C in a covered cup for 20 minutes if

$$m \frac{180 \times 10^3 \text{ J}}{\text{kg}} = \frac{17 \text{ J}}{\text{sec m}^2 \text{ }^\circ\text{K}} (0.02 \text{ m}^2)(53 - 20^\circ\text{C})(1200 \text{ sec}),$$

$$m = 0.07 \text{ kg}.$$

We will need a few ounces of beeswax. Even though there are still major unknowns in this product, the idea merits further development. One important consideration will be how to ensure that heat is quickly transferred from the freezing wax to the hot coffee.

5.3 IZBOR NA OSNOVI MANJ OBJEKTIVNIH KRITERIJEV

Poleg objektivnih kriterijev (kemijskih in inženirskih), moramo pri končnem izboru upoštevati tudi subjektivne kriterije in sprejemati bolj subjektivne odločitve.

Subjektivno se odločamo, ko izbiramo na osnovi kriterijev, ki so po naravi subjektivni. Na primer: Kaj imajo ljudje radi? Koliko jim kaj pomeni?

Subjektivno se odločamo tudi takrat, ko izbiramo na osnovi objektivnih kriterjev za produkt, ki pa se med seboj zelo razlikujejo ("Izbor med jabolki in hruškami"). Na primer ko izbiramo oziroma iščemo kompromis med ceno in tehničnimi specifikacijami produkta. Cena in učinkovitost produkta sta objektivna kriterija. Izbira med njima, pa ne more biti objektivna.

Kdaj sprejemamo subjektivne odločitve?

Navadno s sprejemanjem subjektivnih odločitev odlašamo. Na primer nima smisla, da se sprašujemo o tem ali bo izgled produkta všeč potrošnikom, če bomo kasneje ugotovili, da bi nam (gospodarski družbi) proizvodnja in prodaja takšnega produkta pomenila ekonomsko izgubo.

Prvi in najpomembnejši trenutek, ko se subjektivnemu ocenjevanju ne moremo več izogniti, nastopi takrat, ko določamo kriterije za izbirno matriko. V izbirni matriki upoštevamo vse kar je zelo

pomembno za uporabnike - poleg objektivnih kriterijev (cena, tehnična smiselnost...) upoštevamo tudi subjektivne kriterije (hrup, vpliv na okolje...). Pri tem se je potrebno zavedati, da se uporabniki oziroma tržišča lahko pomembno razlikujejo med seboj po potrebah in zahtevah. (Na primer prebivalcem Anglije se ne bodo pretirano obremenjevali z vlago v njihovih domovih, kar pa je lahko za prebivalce Kuvajta glavna skrb).

Sprejemanju subjektivnih odločitev se ne moremo izogniti, kadarkoli primerjamo različne objektivne kriterije med seboj - ko posameznim kriterijem pripisujemo pomembnost z utežnimi faktorji. Utežni faktorji morajo temeljiti na potrebah in željah uporabnika. (Na primer Francoz bo trdil, da najpomembnejša lastnost rdečega vina uravnoveženost, Avstalec bo trdil, da mora biti "veliko", študentu pa je pomembno, da ni predrago.)

Subjektivnosti se ne moremo izogniti, ko ocenjujemo subjektivne kriterije posameznih idej, ko se sprašujemo kaj je lepše, udobnejše, okolju prijaznejše...

Pri subjektivnem odločanju se je potrebno vedno zavedati, da naše osebno mnenje ni nujno tudi mnenje večine!

Kako sprejemamo subjektivne odločitve?

Pri določanju kriterijev za izbirno matriko ne smemo spregledati nobene ključne potrebe ali zahteve uporabnika, saj so lahko posledice za uspešnost produkta katastrofalne. Upoštevati je potrebno sledeče:

- Kriteriji morajo biti med seboj neodvisni. (Na primer: Plezalno kladivo naj bo lahko in trdno. Masa in trdnost nista neodvisna kriterija. Boljši kriterij je: Plezalno kladivo naj bo iz materiala z visokim razmerjem trdnost/masa.)
- Kriteriji se ne smejo podvajati. (Na primer pri izboru ideje za shranjevanje nevarnih odpadkov sta neposrečeno izbrana kriterija varnost in odziv javnosti. Odziv javnosti bo odvisen od varnosti.)
- Upoštevani morajo biti vsi najpomembnejši kriteriji. Za uporabnika najpomembnejši kriteriji! Informacije dobljene z raziskavo trga in pomočjo ekspertov so dragocene.

Zakaj uporabljamo izbirne matrike?

Prednosti uporabe izbirnih matrik so:

- Uporaba izbirne matrike nas sili k upoštevanju posameznih korakov v procesu izbora končne ideje. Pri tem argumente za sprejete odločitve dokumentiramo. Po izboru končne ideje ni povratka. Stroški projekta (testiranje, razvoj prototipov, raziskave trga) močno narastejo. Po izboru ideje želimo (povečan pritisk managementa), da bi bil nov produkt čim prej na trgu.
- Ocenjevanje idej sili jedro projektnega team-a k bolj učinkovitemu in zavzetemu delu. Iščejo se še druga mnenja. Ocenjevanje idej, ker je ocenjevalcev več, preprečuje "vsiljevanje" volje posameznikov.
- Ocene idej nam povejo veliko. Povejo nam, kakšne in kolikšne so slabosti in prednosti vsake posamezne ideje. Mogoče se ponudi možnost kombinacije različnih idej in je zato končna ideja bistveno boljša.

Poleg uporabe izbirne matrike poznamo še druge načine izbora končne ideje:

- Lahko se odločimo, da končno idejo namesto nas izbere nekdo drug. Na primer manager ali kupec produkta.
- Lahko se odločimo intuitivno (Primer je tiskarski stroj.).

- Lahko izdelamo prototipe in testiramo ideje. Zanesljivost je v tem primeru velika, je pa to dražje in časovno potratno.

Primeri (Vir: E. L. Cussler in G. D. Moggridge, Chemical Product Design, Cambridge University Press, Cambridge, 2001.)

EXAMPLE 4.3-1 MONARCHY SUBSTITUTION

As we have described the selection of princes, we take as an example the replacement of the British Prince of Wales. First we must establish our selection criteria. There are really only two things required of a prince. First, good health: monarchy is a symbol of stability and this is badly undermined if royalty keep dying off. Second, good looks: a prince must meet the demands of TV appearances, damsels in distress, and so on. We will weight these criteria equally. Next we need some ideas. We could do worse than look at the unemployed royal families of Europe; the most noble are the Hapsburgs and the Romanovs. How do they match up to our requirements? We will use the current market leader, Prince Charles, as our benchmark, giving him the average score of 5.5 on each criterion. On looks, the Romanovs score big. The Hapsburgs sadly suffered from a notorious chin (perhaps as a result of the severely limited breeding opportunities available to European royalty). On health, the Hapsburgs perform excellently. The penultimate Emperor, Francis Joseph, died in 1916 at the age of 87, having ruled for 68 years. Sadly, the Romanovs score poorly on health. Their particular genetic defect was hemophilia. The Tsarevich Alexis was so infirm that he often had to be carried at state functions by the sailor Darevenko. We might produce the selection matrix in Table 4.3-1. Interestingly, all three options have the same scores, but for widely different reasons. Changing these scores implies changing the weighting factors, or introducing new criteria for a successful prince.

TABLE 4.3-1 Selecting a Prince of Wales

Parameter	Weighting Factor	Prince Charles	Hapsburg Prince	Romanov Prince
Health	0.5	5.5	10	1
Looks	0.5	5.5	1	10
Total		5.5	5.5	5.5

Note: The incumbent and two alternatives have similar scores but for very different reasons.

EXAMPLE 4.3-2 THE HOME VENTILATOR

In older houses, the mean residence time of air is often around 40 minutes. Demands for draft reduction and energy efficiency mean that houses are increasingly well insulated and sealed, so the mean residence time can be 12 hours in modern houses. This is good for comfort and efficiency, but it is unhealthy. The air inside well-sealed houses contains excess CO₂, CO, radon, and formaldehyde. (This last evaporates from carpets and drapery, particularly when they are new.) The formaldehyde is often the first to reach dangerous levels. However, cigarette smoke is a very efficient scavenger of radon, so in the houses of smokers radon may be an even greater problem. Currently, there is no legislation regulating the

turnover time of air in homes. Anomalously, fresh air replacement is required every 3 hours for laboratory animals in the U.S. It seems likely that legislation for humans will soon catch up.

Assuming that complete air replacement is required every 3 hours, is it possible to combine the economics and comfort of a tight house with the health advantages of a leaky one?

SOLUTION

The simplest answer is to open a window! This of course destroys much of the benefit, but it is easily achieved and will have the desired health benefit. We will take as our benchmark product an automatic window opening device that monitors air flow into the house and keeps the opening of a window at a level such as to maintain the flow necessary for a 3-hour exchange of air. This device will be cheap and easy to retrofit into “tight” houses.

Can we do better than this? Another approach is to exchange the air through a heat exchanger to minimize energy loss. This will be more comfortable, reducing the drafts to be expected as a result of an open window. A disadvantage, particularly in very cold climates, is that the incoming air will be very dry whereas that leaving the house will have a significant water content. Thus the house will dry out and become uncomfortable. One possible solution, to evaporate water, will be expensive because of the latent heat required. An alternative is to devise a ventilator that exchanges both heat and water vapor from the outgoing air stream into the incoming one. Although such units have not been commercially constructed, available literature suggests that polyimide membranes could be used for such an application.

We have two alternative products to compare to our benchmark: heat exchange with water evaporation and simultaneous heat and mass exchange. We will start by using an engineering analysis to estimate the feasibility, cost, and energy saving for each product. We will then use a decision matrix in order to assess the product’s value relative to the benchmark, including some subjective criteria. We perform our analysis for the cases of Minnesota and Cambridge. In what follows, plain text refers to Minnesota and italics to Cambridge.

SETTING UP THE PROBLEM. We assume an average house in Minnesota has a floor area of 250 m². *In Cambridge, houses are smaller, perhaps half the size.* Thus we find:

$$\text{Volume of air in house} = 250 \text{ m}^2 \times 3 \text{ m ceilings} = 750 \text{ m}^3 \text{ (375 m}^3\text{)}.$$

Number of moles of air in house, n , is given by

$$\Delta H = n \underbrace{\left(\frac{7}{2}R\right)}_{\text{gas heat capacity}} \Delta T = 29,000 \text{ kJ (7,300 kJ)},$$

where $(7/2)R$ is an estimate of the gas heat capacity.

This is our energy cost per complete air exchange in terms of specific heat. But what about humidification and latent heat?

Now we assume the external relative humidity is 0% (60%). That inside is the same, a comfortable 20%, in both Minnesota and Cambridge. The energy required to evaporate water to reach this humidity is

$$\Delta H(\text{vap}) = (y_{\text{H}_2\text{O}}^{\text{in}} - y_{\text{H}_2\text{O}}^{\text{ex}}) \Delta H_{\text{vap}} = 9000 \text{ kJ}$$

where ΔH_{vap} is the specific enthalpy of evaporation of water; and $y_{\text{H}_2\text{O}}^{\text{in}}$ and $y_{\text{H}_2\text{O}}^{\text{ex}}$ are the mole fraction of water vapor inside and outside the house, respectively.

In Cambridge, the external mole fraction of water is

$$y_{\text{H}_2\text{O}}^{\text{ex}} \approx 0.6(0.0087) = 0.0052,$$

and the internal mole fraction is

$$y_{\text{H}_2\text{O}}^{\text{in}} = 0.2(0.023) = 0.0046,$$

where 0.0087 bar and 0.023 bar are the saturated vapor pressures of water at 5°C and 20°C, respectively.

Therefore, we expect on a “normal” day in Cambridge that there will be no need to replenish the house’s water content. Of course, the weather fluctuates a lot. On some days it may be desirable, but on average the cost will be low.

Back in Minnesota, the heating costs for the tight house, with air turnover every 12 hours, are

$$\begin{aligned} & \frac{(29,000 + 9000) \text{ kJ}}{12 \text{ hr}[3600 \text{ (sec/hr)}]} \times (24 \times 30) \frac{\text{hr}}{\text{month}} \times \frac{\approx 0.03}{\text{kwhr}} \\ & = \approx 19 \text{ per month } (\approx 3.65 \text{ per month}). \end{aligned}$$

The heating costs for a house with a window opener, with air turnover every 3 hours, are

$$\begin{aligned} & \frac{(29,000 + 9000) \text{ kJ}}{3 \text{ hr}[3600 \text{ (sec/hr)}]} \times (24 \times 30) \frac{\text{hr}}{\text{month}} \times \frac{\approx 0.03}{\text{kwhr}} \\ & = \approx 76 \text{ per month } (\approx 14.60 \text{ per month}). \end{aligned}$$

We expect that a heat exchanger recovers 70% of the specific heat. The heating for a house with such a heat exchanger plus humidification and a 3-hour air turnover costs

$$\begin{aligned} & \frac{(0.3 \times 29,000) + 9000}{3 \times 3600} \times (24 \times 30) \times 0.03 \\ & = \approx 35 \text{ per month } (\approx 4.40 \text{ per month}). \end{aligned}$$

Finally, we expect that the heat and water vapor exchanger recovers 70% of both heat and water vapor. The cost of heating a house with both heat and mass exchanger and a 3-hour air turnover is

$$0.3 \times 76 = \approx 23 \text{ per month } (\approx 4.40 \text{ per month}).$$

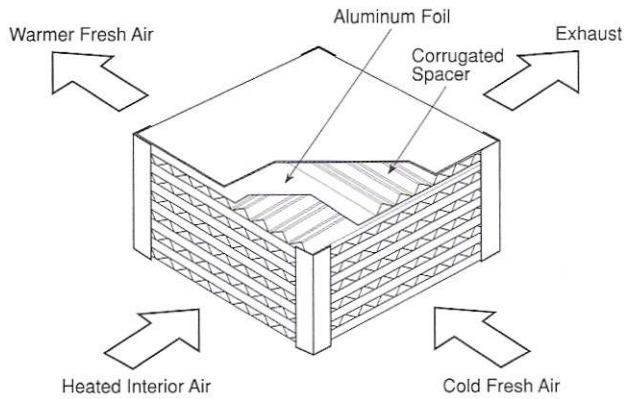


Figure 4.3–1. Schematic of a Domestic Crossflow Heat Exchanger. Warm, stale inside air is used to heat cold, fresh outside air. This heating, which reduces domestic energy use, takes place across sheets of aluminium foil.

MAKING THE HEAT EXCHANGER. We are trying to build a unit with 70% efficiency for heat recovery. We will assume a countercurrent unit with parallel plate geometry for simplicity: a schematic is shown in Figure 4.3–1. In such a device the molar flow rate of air, GA , is

$$GA = \frac{33,500 \text{ mol}}{3 \text{ hr} \times 3600 \text{ (sec/hr)}} = 3.1 \text{ mol}^{-1} (1.6 \text{ mol}^{-1}).$$

Total heat transfer rate across the whole exchange surface is

$$Q = GA\bar{C}_p(T_{\text{out}} - T_{\text{in}}) = 3.1 \times (7/2R) \times 21 = 1900 \text{ W} (440 \text{ W}).$$

Now consider the heat flux per unit area, Q :

$$Q = UA\Delta T;$$

where ΔT is the temperature drop across the heat exchanger surface, a constant 9°C (5.5°C) throughout the unit. The overall heat transfer coefficient, U , is given by

$$U = \frac{1}{1/h_{\text{ex}} + 1/h_{\text{wall}} + 1/h_{\text{in}}},$$

where h_{ex} , h_{wall} , and h_{in} are the heat transfer coefficients of the exhaust air, the wall, and the entering air, respectively.

The exchange surface can be constructed of 1-mm-thick aluminium sheet: this will have a large h_{wall} and a negligible thermal resistance. Thus the h_{wall}^{-1} term can be ignored. The heat transfer coefficient for the incoming air, h_{in} , will equal that for the exhausting air, h_{ex} . Thus

$$U = \frac{1}{2}h_{\text{ex}}$$

but

$$h_{\text{ex}} = k_T / \delta,$$

where k_T is the thermal conductivity and δ is the film thickness over which heat transfer is occurring.

If we assume that the flow is laminar and that we have parallel plate geometry, then δ is approximately 1/4 of the channel dimension in the heat exchanger (i.e., halfway to the middle). Let us assume a channel dimension of 3 mm, so

$$U = \frac{1}{2} h_{\text{ex}} = \frac{1}{2} \left(\frac{k_T}{1/4 \text{ channel}} \right) = \frac{1}{2} \frac{0.026 \text{ W m}^{-1} \text{ K}^{-1}}{1/4(0.003) \text{ m}} = 17 \text{ W m}^{-2} \text{ K}^{-1}.$$

The area, A , required for the exchanger is now

$$A = \frac{1900}{17 \times 9} = 12 \text{ m}^2 \text{ (5 m}^2\text{)}.$$

This type of simple parallel plate heat exchanger, a well-established technology, can be built for around ≈ 6 per m^2 . The production cost will be about ≈ 72 (≈ 30) and we might expect to sell the units for perhaps eight times this, a few hundred pounds.

Before we proceed, we should check that the flow is indeed laminar. To do so, we recognize that the volume of heat exchanger is $12 \times 0.003 = 0.036 \text{ m}^3$.

If the exchanger is cubic, the cross sectional area available for flow in each direction is about

$$\begin{aligned} &= 0.5(0.036)^{2/3}, \\ &= 0.055 \text{ m}^2. \end{aligned}$$

The superficial velocity of air v is given by

$$v = \frac{750 \text{ m}^3}{3 \text{ hr} \times 3600 \text{ (sec/hr)}} \times \frac{1}{0.05 \text{ m}^2} = 1.27 \text{ ms}^{-1}.$$

Thus the Reynolds number is

$$\text{Re} = \frac{dv}{\nu} = \frac{1.27 \times 0.003}{1.3 \times 10^{-5}} = 300.$$

That is, the flow is probably laminar.

MAKING THE HEAT AND MASS EXCHANGER. The equipment shown in detail in Figure 4.3–2 is similar to the heat exchanger shown in Figure 4.3–1. However, the problem is now more complex because we have simultaneous heat and mass transfer. We will use the same approach, looking at two key equations:

1. The total transfer across the whole exchanger.
2. The rate of transfer per unit area.

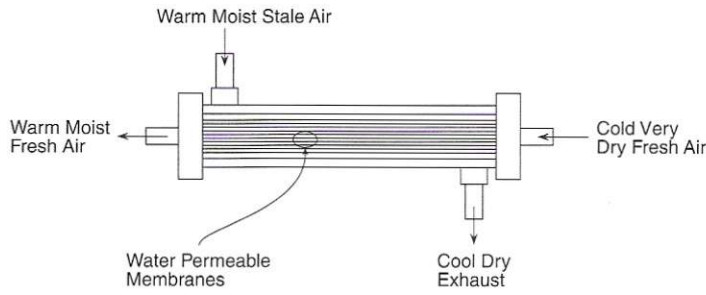


Figure 4.3-2. Schematic of a Countercurrent Heat and Mass Exchanger. Warm, conditioned, but stale inside air heats and humidifies cold, dry, fresh air. A water permeable membrane replaces the aluminium foil of the previous figure.

There will now be two sets of these two key equations, one for heat transfer and one for mass transfer.

We will assume the same geometry as for the heat exchanger, but replace the aluminium exchange surface with a 30- μm -thick polyimide membrane. Such a membrane is selective for water transport and has a negligible resistance to water exchange. It is also sufficiently thin that its thermal resistance can be ignored (as was done for the aluminium in the normal heat exchanger).

We will first look at heat transfer and examine in detail a point on the exchange surface. The heat flux, q , at such a point is given by a combination of an enthalpy term (heat carried by water moving across the membrane) and a conductive term:

$$q = \underbrace{C_p n_A (T - T_0)}_{\text{enthalpy term}} - \underbrace{k_T \frac{\partial T}{\partial z}}_{\text{conductive term}}.$$

We cannot separate heat and mass transport. However, we can link them by considering the total flows across the whole exchange unit. As before, the total heat flow, Q , is

$$Q = qA = GA \bar{C}_p (T_{\text{out}} - T_{\text{in}}) = 1900 \text{ W}.$$

The total molar flow of water, $n_A A$, is

$$n_A A = GA(y_{\text{out}} - y_{\text{in}}) = GA y_{\text{out}}.$$

Thus

$$\frac{n_A}{q} = \frac{y_{\text{out}}}{\bar{C}_p (T_{\text{out}} - T_{\text{in}})}.$$

Notice that this is only true because we have a countercurrent exchanger with a flat plate geometry and equal flow rates in and out. Thus both mass and heat fluxes are the same at any point on the exchange surface.

The heat flux now becomes

$$q = \left(\frac{y_{\text{out}}}{T_{\text{out}} - T_{\text{in}}} \right) (T - T_0) q - k_T \frac{\partial T}{\partial z},$$

$$q \left[1 - \frac{y_{\text{out}}(T - T_0)}{(T_{\text{out}} - T_{\text{in}})} \right] = -k_T \frac{\partial T}{\partial z},$$

$$q[z]_0^\delta = \frac{(T_{\text{out}} - T_{\text{in}})}{y_{\text{out}}} k_T \left\{ \ln \left[1 - \frac{y_{\text{out}}(T - T_0)}{(T_{\text{out}} - T_{\text{in}})} \right] \right\}_{T_m = T_b + 1/2\Delta T}^{T_b},$$

$$q = \frac{k_T (T_{\text{out}} - T_{\text{in}})}{\delta y_{\text{out}}} \ln \left(1 + \frac{y_{\text{out}} 1/2\Delta T}{T_{\text{out}} - T_{\text{in}}} \right), \quad \text{choosing } T_0 = T_m.$$

Because $y_{\text{out}} < 0.005$ and ΔT is of the same magnitude as $(T_{\text{out}} - T_{\text{in}})$, we have

$$\ln \left(1 + \frac{y_{\text{out}} 1/2\Delta T}{T_{\text{out}} - T_{\text{in}}} \right) \approx \frac{y_{\text{out}} \Delta T / 2}{T_{\text{out}} - T_{\text{in}}},$$

and so

$$q \approx \frac{k_T \Delta T}{\delta} \frac{1}{2} = U \Delta T.$$

That is, the result is identical to the previous (no mass transfer) case. This means that the enthalpy term in the heat transport equation is small compared with the conductive term.

Once again,

$$A = 12 \text{ m}^2$$

for 70% efficiency of heat exchange.

Now consider the mass transfer. We want to calculate y_{out} for an exchange area of 12 m^2 . In other words, we want to check that the efficiency of water exchange is at least 70%.

The molar flux in a binary system is given by the following mass transfer equation:

$$n_A = (vc_A + j_A) = (n_A + n_B)y_A - cD(\partial y_A / \partial z),$$

where water is A and air is B. But y_A is close to zero because water is dilute in air. In general both c and D are temperature dependent. Thus in principle we need to incorporate the spatial variation of (cD) . However, the range of temperature in the heat exchanger is small ($\pm 15^\circ\text{C}$), so (cD) does not vary much. Thus we integrate to find

$$n_A = \frac{p}{RT} D \frac{\Delta y}{2\delta}.$$

We now return to the equation for total molar flow across the exchanger:

$$n_A A - G A y_{\text{out}} = G A (0.005 - \Delta y),$$

$$\frac{p}{RT} D \frac{\Delta y}{2\delta} A = G A (0.005 - \Delta y).$$

TABLE 4.3-2 Summary of Objective Factors for House Ventilation

Parameter	Costs	
	Minnesota	Cambridge
House with 3-hour air turnover	≈76 per month	≈14.60 per month
+Heat exchange (and humification)	≈35 per month	≈4.40 per month
+Heat and mass exchange	≈23 per month	≈4.40 per month
Unit price for heat exchange unit	≈500 + installation	≈250 + installation
Unit price for heat + mass exchange unit	≈500 + installation	≈250 + installation
Payback time: heat exchange unit	12 months	25 months
Payback time: heat + mass exchange unit	9 months	25 months

Note: Payback times are months of Winter.

For an N₂-H₂O mixture at 308 K, $D = 0.256 \text{ cm}^2 \text{ s}^{-1}$. Thus

$$\frac{101325}{8.314 \times 278} \times 0.256 \times 10^{-4} \frac{\Delta y}{2 \times (1/4 \times 0.003)} \times 12 = 3.1(0.005 - \Delta y),$$

$$\Delta y = 0.0013.$$

The efficiency of water exchange in our 12 m² polyimide exchanger is

$$\frac{0.005 - 0.0013}{0.005} \times 100\% \approx 70\%.$$

Thus both heat and mass exchange efficiency targets are met simultaneously for this 12 m² polyimide exchanger.

We summarize the results of these calculations in Table 4.3-2. This summary recognizes that the cost of polyimide membranes is likely to be greater than the price of aluminium sheet. However, most of the cost of exchanger units can be expected to be in the construction, so we can assume that the cost of production for the heat and mass exchanger is similar to that for the heat only exchanger already estimated. On the purely objective criterion of economic benefit, both heat and heat/mass exchangers look like winners in Minnesota. The situation is less clear in Cambridge: the heat exchanger may be viable, but the heat/mass exchanger has little advantage.

However, this analysis is not sufficient to make a decision. There are other, subjective factors to consider. For simplicity, we restrict ourselves to three additional ones: health (as air quality), comfort, and noise. We now have five criteria: heating cost, capital cost, health, comfort, and noise. We have separated heating cost and capital cost rather than include a single economic criterion because we might wish to give slightly higher weight to the reduction of heating bills on environmental grounds. We will now use these five criteria to illustrate how a decision matrix can help in the final selection process.

Table 4.3-3 exemplifies the decision matrix we can draw up. The values in this table include both the engineering results of Table 4.3-2 and the subjective factors. These merit discussion.

TABLE 4.3-3 Decision Matrix for House Ventilation

Parameter	Weight	3-hour Exchange (Benchmark)	Heat & Mass Transfer	Heat Transfer & Humidification
Heating Cost	0.3	5	10 (7)	8 (7)
Capital Cost	0.2	5	3 (3)	3 (3)
Health Benefit	0.2	5	5 (5)	5 (5)
Comfort	0.2	5	10 (7)	8 (6)
Noise	0.1	5	2 (2)	2 (2)
Total		5.0	6.8 (5.3)	5.8 (5.1)

“Health” scores identically for all products: it is redundant. We have included it for completeness and it would certainly be needed if a larger range of products was being considered. It probably should be dropped.

The results for comfort are more interesting. Both exchangers give humidity control when the outside is dry. However, the heat and mass exchanger also gives the potential for humidity reduction (in summer). Comfort is not such a large problem in Cambridge, where conditions are less extreme and so the scores are more moderate. However, both exchangers require a pumping system, which may result in irritating noise. Notice that we have scored the benchmark, which is silent, 5: this inevitably leads to scale compression. We could avoid this, perhaps by scoring the benchmark differently. The conclusions from this decision matrix are pretty much what we already know. In Cambridge, the viability of these exchangers is marginal. In Minnesota, their viability looks good. The heat and mass transfer unit looks somewhat better than heat transfer with humidification.

This conclusion includes consideration of factors beyond the economic and engineering criteria. We have been forced to think hard about what matters for a home ventilation system and how much to weight each criteria. In doing so we almost certainly will have had to talk to our potential customers, component manufacturers, and so on. The next stage of development will be to build a prototype – this will be expensive. It is important to do some consultation and hard thinking first, and the discipline of the decision matrix ensures that we do these things.

5.4 TVEGANJE PRI IZBORU PRODUKTA

V nekaterih primerih ne moremo biti povsem prepričani, da bo nov produkt deloval oziroma da ga bomo znali narediti. Lahko so vprašljivi detajli kemijske sinteze, lahko nismo prepričani ali nam bo sintezo (ki smo jo uspeli narediti v laboratoriju) uspelo voditi v industrijskem reaktorju... V teh primerih izbiramo med idejami z različnimi stopnjami tveganja. Takrat se moramo vprašati, kako resno je tveganje in kako bo tveganje vplivalo na produkt. Želeli bomo zmanjšati tveganje.

Ocena tveganja

Ocena tveganja vključuje tri korake. Najprej različna tveganja identificiramo, zberemo ter določimo stopnjo posameznega tveganja. Nato ugotovimo ali lahko tveganja opišemo (ocenimo) s pomočjo kemijskih in inženirskih orodij ali pa samo predstavljajo negotovost. Potem moramo predvideti ali bodo zaradi tveganj potrebni višji finančni vložki v razvoj produkta ter ali bo za razvoj potrebno bistveno več časa.

Ko identificiramo potencialna tveganja postopamo podobno, kot smo postopali, ko smo iskali ideje za nov produkt. Pri tem sodeluje projektni team in drugi zaposleni v organizaciji, še posebej zaposleni v proizvodnji, ki so bili do sedaj manj vključeni v delo pri razvoju novega produkta. Ponovno moramo kontaktirati uporabnike, posebej vodilne uporabnike. Ponovno se lahko obrnemo na zunanje svetovalce.

Ko imamo seznam potencialnih tveganj, moramo določiti verjetnost in posledice vsakega tveganja. To počne jedro projektnega team-a. Verjetnost tveganja ocenjujemo z vrednostmi od 0 do 1 ($< 0,3$ – zanemarljiva verjetnost, $0,5$ – znatna verjetnost, $> 0,9$ – zelo velika verjetnost).

Nato mora jedro projektnega team-a posameznim tveganjem pripisati posledice. Tudi pomembnost posledic ocenjujemo z vrednostmi od 0 do 1 ($< 0,3$ – majhne posledice, $0,5$ – znatne posledice, $> 0,9$ – zelo velike posledice, tako velike, da povzročijo propad projekta).

Koristno je, da vsak član team-a sam pripisuje vrednosti (verjetnosti in posledic) posameznim tveganjem. Na tak način morajo posamezniki intenzivno razmisliti o vsakem tveganju posebej. Končne vrednosti (verjetnosti in posledic) pa se določi na skupnem sestanku jedra projektnega team-a s konsenzom.

Ko so definirane verjetnosti in posledice, določimo stopnjo tveganja. Stopnja posameznega tveganja je produkt njegove verjetnosti in posledic. Tveganja, ki imajo zanemarljivo stopnjo, zanemarimo. Tveganja višje stopnje (recimo $> 0,5$) pa upoštevamo v nadaljnjem postopku. Tudi ko se odločamo, kakšno stopnjo tveganja lahko zanemarimo, je potreben konsenz.

Po določitvi stopenj tveganj tveganja z znatno in višjo stopnjo razdelimo na tista, ki jih lahko pojasnimo s pomočjo kemijskih in inženirskih orodij (Primeri: obstaja možnost, da uporabljena korelacija za prenos toplote ni primerna..., kemijska reakcija je lahko počasnejša od pričakovane..., produkt bo lahko imel previsoko viskoznost...), in tista, ki jih s pomočjo kemijskih in inženirskih orodij ne moremo pojasniti. Slednja so pogosto posledica trga in politike (Primeri: na trgu obstaja samo en dobavitelj surovine, ki jo nujno potrebujemo za produkt..., odziv lokalne skupnosti na širitev tovarne z namenom postavitve nove proizvodne linije...). V primeru, ko lahko uporabimo kemijska in inženirska orodja, to naredimo na enak način kot v prejšnjih poglavjih.

Naloga jedra projektnega team-a je tudi, da predvidi ali bodo zaradi identificiranih tveganj potrebni višji finančni vložki v razvoj produkta ter predvsem koliko več časa bo zato za razvoj potrebno (Na primer če obstaja verjetnost, da so bile v izračunih uporabljene korelacije za prenos toplote, ki ne dajejo realnih napovedi, bo inženir potreboval šest mesecev, da razvije popravljene korelacije.).

Zgoraj opisana ocena tveganja je povsem primerna takrat, ko med seboj primerjamo podobne kemijske produkte, ki niso zelo izpostavljeni tveganju. Manj je primerna takrat, ko primerjamo "varne" (poznane) tehnologije z novimi tehnologijami, ki se še lahko izkažejo za popolnoma neprimerne. V tem primeru, ko je verjetnost za neuspeh produkta velika ali pa so posledice tveganj katastrofalne (na primer eksplozija), je potrebna predvsem zelo velika previdnost in natančnost v vseh korakih načrtovanja produkta.

Ravnanje v primeru tveganja

Možnosti sta dve:

1. Zmanjšamo stopnjo tveganja preden nadaljujemo z razvojem produkta.
2. Sprejmemo tveganje in nadaljujemo z razvojem produkta.

Prva možnost je tradicionalna metoda obvladovanja tveganja. Spet potrebujemo več idej za zmanjšanje tveganja, izmed katerih izberemo najboljšo. Potrebne so raziskave, eksperimenti, načrtovanje procesov, testiranja trga... Postopek je učinkovit, vendar dolgotrajen in drag. Lahko celo

ogrozi uspešnost projekta za razvoj novega produkta. Projekt lahko postane neekonomičen, konkurenca nas lahko prehití, potrebe na trgu se lahko spremenijo... Če predstavlja zmanjševanje tveganj tveganje za projekt, se lahko odločimo, da projekt v tej fazi zaključimo.

Druga možnost, prav zaradi zgoraj omenjenih razlogov (čas in denar), ni redkost. Seveda ni mogoča takrat, ko so pomembno ogroženi zdravje, okolje in varnost. Slednje urejajo številni zakoni, pravilniki...

Da se v čim večji možni meri prepreči visoke investicije v projekt, ki je še vedno tvegan, se uporabljata dve priporočili:

1. Če je tveganje visoko, vzdržuj nizke investicijske stroške. Povečaj jih, ko stopnja tveganja pada.
2. Razdeli tvegan projekt na več delov ali faz. Odloči se, pri kateri fazi ga boš opustil, če bo neperspektiven.

Primer: Razvoj naprave, ki opravlja kemijsko spremembo

Najprej še enkrat preigramo inženirske ocene, ki smo jih naredili. Pri tem ne uporabljamo večjih poenostavitev in uporabljamo najbolj pesimistične vrednosti fizikalnih lastnosti. Če je ideja še vedno perspektivna, izdelamo realistični model primeren za laboratorijski nivo. Na modelu opravimo eksperimente in preverimo smiselnost inženirskih ocen. Če projektu še vedno dobro kaže, izdelamo pilotno napravo, na kateri pridobimo podatke za končni izbor.

Primer: Padanje stopnje tveganja pri razvoju novega zdravila (Tabela 4.4-1)

Na začetku razvoja je tveganje visoko, ker je učinkovitost zdravila negotova. Če so rezultati kliničnih poskusov pozitivni in takšni ostajajo, tudi tveganje pada. Ko je sinteza zdravila bolj dorečena, postaja tudi vrednost zdravila bolj gotova. Tveganje je najnižje za zrel produkt s skrbno nadzorovano kvaliteto.

Tabela: Tveganje pri razvoju novega zdravila (Vir: E. L. Cussler in G. D. Moggridge, *Chemical Product Design*, Cambridge University Press, Cambridge, 2001.)

Status	Chemical Status	Quality Status	Risk
Preclinical efforts	Major process work needed	Few methods available	High
Phase I clinical trials	Laboratory procedures available	Analytical development necessary	High
Phase II to Phase III clinical trials	Pilot plant production	Analytical methods in place	Moderate
Late-stage clinical trials	Production process fixed	Methods validated	Low
Mature product	Plant process available	Quality control key	Low
Generic drug	Patents available	Methods sometimes available	Moderate

Source: Charles M. Boland, Cedarburg Laboratories, quoted in *Chemical and Engineering News*, Feb. 14, 2000.

Primeri (Vir: E. L. Cussler in G. D. Moggridge, *Chemical Product Design*, Cambridge University Press, Cambridge, 2001.)

EXAMPLE 4.4-I POWER FOR ISOLATED HOMES

In many European countries, electricity companies are required to provide power to homes at a fixed connection fee and standard cost per unit consumed, regardless of the homes' remoteness. Laying many kilometers of cabling to connect a single house to the national grid is clearly uneconomic.

Investigate alternative sources of electric power for isolated homes.

SOLUTION

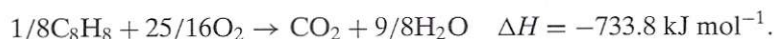
We briefly review how one might follow the design template suggested in this book to reach the stage at which risk should be considered.

NEEDS. We will not attempt to provide electric heating, but will aim to fulfil all other normal domestic requirements, such as cooking, lighting, cooling, and so on. A little research indicates typical power requirements to average 3 kW, with a peak loading of 15 kW (mainly a result of cooking). This provides our specification.

IDEAS. There are a very large number of ways of generating electricity, some obvious (such as hydroelectric power), others more bizarre (natural gas from manure). Idea generation and initial screening might lead one to consider four leading contenders: a diesel generator, wind power, solar power, and a fuel cell.

SELECTION. For us, as the electricity provider, the primary selection criterion is going to be cost, both in terms of capital and the running cost of providing the specified power. (Remember we can only charge the standard, national rate.) Clearly our solution must also be acceptable to the consumer.

DIESEL GENERATOR. A 15-kW generator costs around \$6500. Running cost can easily be estimated from the price of gasoline if we assume an efficiency of 30%. The combustion of gasoline is



At the efficiency given, this suggests that

$$\frac{733.8 \text{ kJ/mol}^{-1}}{1/8(104 \text{ g/mol})} \times 800 \text{ g L}^{-1} \times 4 \text{ L/gal} \times (0.3)/\$1.60 \text{ per gallon} \\ \approx 34,000 \text{ kJ per } \$.$$

In a year, we need

$$3 \text{ kW}(3600 \text{ s/hr}) 24 \text{ hr/day} (365 \text{ days/year}) = 95 \times 10^7 \text{ kJ/year}.$$

Thus our fuel cost for the diesel generator is

$$\frac{95 \times 10^7}{34,000} = \$2800/\text{year}.$$

Although noise might be an issue, we can expect a diesel generator to work well. Because it is very well-established technology, we will use it as our benchmark.

WIND POWER. A 3-kW generator has 3-m-diameter blades and costs around \$5000. We must make use of a battery to provide the peak power load. (This will probably be necessary anyway to smooth the uneven wind energy.) We need two such generators. Once installation and battery costs are included, we are unlikely to escape with capital costs under \$20,000. Running costs will be negligible. Aesthetics could be an important issue.

SOLAR POWER. Even the most efficient solar cells only manage to convert around 10% of the absorbed solar energy. Furthermore, we can only use the cells on average 12 hours per day, less in winter when power requirements will be high. Incoming solar energy is about 100 W m^{-2} . To supply our 3-kW average power, we will need:

$$\frac{(24 \text{ hr}/12 \text{ hr})3 \text{ kW}}{[0.1(\text{kW}/\text{m}^2)]0.1 \text{ efficiency}} = 600 \text{ m}^2 \text{ of solar panels.}$$

Again, we will require a battery, the efficiency of which we have ignored. In winter, the power available will be lower. Solar panels cost around \$100/m², giving a capital cost of at least \$60,000. We reject this idea on economic grounds.

FUEL CELL. Although the running cost will parallel that of the diesel generator, we can now avoid the limitations of Carnot efficiency and hope to reach 70% efficiency. Therefore running cost is

$$\$2400 \times 0.3/0.7 = \$1000/\text{year.}$$

Fuel cells are still substantially more expensive than the equivalent conventional generator: we can expect to pay at least \$15,000.

A decision matrix based on the considerations just outlined might leave three contenders: the diesel generator, wind power, and the fuel cell. Before immediately proceeding with the idea that seems most attractive at this stage, we must consider risk.

In this case, the major risks are:

1. Customer acceptability, including noise and environmental considerations;
2. Regulatory acceptability, including pollution and local permission;
3. Maturity of technology; and
4. Reliability.

The third of these takes account of the effort likely to be required to bring the technology to the level where it can be slotted into our application. This risk applies primarily to the fuel cell, a relatively unestablished technology. Fuel cells operate reliably on a large scale with hydrogen fuel, but considerable uncertainty remains about running them reliably at small scale in remote locations with gasoline.

TABLE 4.4–2 Risk Assessment for Wind Power

Risk	Probability	Consequence	Risk Level
Customer acceptability	0.5	0.5	0.25
Regulatory acceptability	0.5	0.7	0.35
Maturity of technology	0.1	0.3	0.03
Reliability	0.7	0.3	0.35

Note: The most serious risks are regulatory and reliability.

The final risk listed reflects the likely costs of repairs and maintenance. Here the wind generator, vulnerable to storms, is likely to be the biggest problem.

Our risk assessment for wind power is given in Table 4.4–2. We are unsure about reducing these risks. Planning restrictions are severe in most of Europe. We cannot change the chances of wind turbines being rejected on aesthetic grounds. Similarly it is hard to alter negative consumer reactions to these unsightly and mesmeric objects. Research may help in improving reliability, but on the whole the wind power option looks risky. We are unlikely to pursue this option.

Our risk assessment for fuel cells is in Table 4.4–3. Maturity of the technology and reliability are significant risks. Both of these could be mitigated by further research. We should proceed by installing reliable diesel generators in the short term. At the same time, we may decide to pursue research into the prospects of the fuel cell option.

EXAMPLE 4.4–2 TAKING WATER OUT OF MILK AT THE FARM

Remote dairies in New Zealand can face major expenses in shipping their milk to a central processing facility, where the milk is largely made into cheese. These dairies would benefit from a method of removing only water to concentrate the milk on the farm. For a typical farm, this means reducing 4000 kg/day raw milk to about 1000 kg/day of concentrate.

Our efforts to resolve this problem have focused on four unit operations: evaporation, absorption, spray drying, and reverse osmosis. Evaporation is the best established, and is used for products such as evaporated milk and condensed milk. It requires careful energy integration. Absorption of water in inorganic and organic gels has significant problems. The inorganic gels that are selective require a lot of energy for the regeneration required for reuse.

The organic gels – such as polyisopropylacrylimide – are easily regenerated but are not sufficiently selective. Spray drying works well only with a feed of 50% solids, much more than that in raw milk. Reverse osmosis membranes foul too easily.

Thus our best idea is evaporation. From an extensive energy analysis, not included here, we decide to run the evaporator at 60°C, using 64°C steam. The steam is produced by sending the 60°C evaporated water through an electrically driven heat pump. (We should remember that a heat pump is approximately a Carnot

TABLE 4.4-3 Risk Assessment for the Fuel Cell

Risk	Probability	Consequence	Risk Level
Customer acceptability	0.3	0.5	0.15
Regulatory acceptability	0.1	0.3	0.03
Maturity of technology	0.5	0.7	0.35
Reliability	0.5	0.5	0.25

Note: These risks assume hydrogen can be handled safely.

engine run backward, using work to move heat up a temperature gradient.) The use of a heat pump reflects the fact that hydroelectric power generation is common in New Zealand, and so electricity is relatively cheap.

Within our choice of evaporation, we have three possible forms of evaporators. The first is the conventional, falling film unit, whose performance is well established and is the sensible benchmark. The second is the centrifugal evaporator, which uses centrifugal force to stabilize thin milk films and hence improve evaporation efficiency. This method works well but the equipment is expensive. The third is a membrane evaporator, where the milk films are stabilized between membranes, which can impede evaporation. This membrane method has not been carefully explored and so has considerable risk.

Select which of these ideas is best. In this selection, compare the evaporators' performance and their risk. Suggest a strategy for product development.

SOLUTION

The solution to this problem implies a total of five steps. The first step is to determine the general specifications that any evaporator must meet. The next three steps are to find the size and cost for each of the three evaporators. The final step is to consider the risk, which in this case is largely associated with the membrane evaporator.

GENERAL SPECIFICATIONS. We must first specify the general heat transfer characteristics of any successful evaporator. Doing so depends on choosing values for the physical properties of milk. Because the evaporation increases the concentrations of milk solids and nonvolatiles, the viscosity increases from 0.9 cp to around 10 cp during evaporation. We will include this change in our calculations, but will assume that other properties of the milk remain close to those of pure water. Thus the milk's density is taken as 1000 kg/m³ and its thermal conductivity is about 0.60 W/m^{°K}.

The total heat transferred, Q , is proportional to the mass evaporated N_1 :

$$Q = UA\Delta T = \Delta \hat{H}_{\text{vap}} N_1,$$

where U is the overall heat transfer coefficient; A is the evaporator area; ΔT is the temperature difference, in this case 4°C; and $\Delta \hat{H}_{\text{vap}}$ is the specific heat

of vaporization at 60°C, here about 2430 kJ/kg. Because N_1 is 3000 kg/day or 0.035 kg/sec,

$$UA = 21 \text{ kW/}^\circ\text{K}.$$

But

$$\frac{1}{U} = 1/h_{\text{steam}} + 1/h_{\text{wall}} + 1/h_{\text{milk}},$$

where h_{steam} is the individual heat transfer coefficient of the condensing steam, around 5000 W/mK; h_{wall} is that of the evaporator surface, typically 20,000 W/mK; and h_{milk} is that of the milk itself. We assume that this is given by

$$h_{\text{milk}} = k_T/\delta,$$

where k_T is the thermal conductivity of the milk, and δ is the milk film thickness. Thus if we can estimate δ , we know h_{milk} and hence U , and so can find the area of a particular evaporator. This will be the key parameter in our selection.

FALLING FILM EVAPORATOR. The first unit we consider is the conventional falling film evaporator. In this unit, the film of milk must spread smoothly over the evaporator surface in order to efficiently use all of the surface. Such a smooth film means that the Weber number, We , must be greater than a critical value of 2:

$$We = (\rho v^2 \delta / \sigma) \geq 2,$$

where ρ is the milk's density, v is its velocity, and σ is its surface tension. For a falling film,

$$v = \rho g \delta^2 / 3\mu,$$

where g is the acceleration due to gravity and μ is the viscosity. Combining

$$\begin{aligned} \delta &= \left(\frac{18\mu^2\sigma}{\rho^2g^2} \right)^{1/5} \\ &= \left[\frac{18(0.1 \text{ g/cm sec})^2 30 \text{ g/sec}^2}{(1 \text{ g/cm}^3)^2 (980 \text{ cm/sec}^2)^2} \right]^{1/5} \\ &= 0.14 \text{ cm}. \end{aligned}$$

To make sure we have a stable film, we assume we want about twice this value, or

$$\delta = 0.3 \text{ cm}.$$

From the above, we then find that h_{milk} equals $[(0.60 \text{ W/mK})/0.003 \text{ m}]$, U is about 200 W/mK, and the evaporator area A is

$$A = 100 \text{ m}^2.$$

This evaporator area, the benchmark for our selection, is large because the temperature difference is small (4°C).

CENTRIFUGAL EVAPORATOR. The centrifugal evaporator uses centrifugal force to keep the milk film smooth, thin, and stable. As the milk film moves outward on the centrifuge disks, its higher viscosity caused by evaporation is more than balanced by the increased centrifugal force. Although the details of the fluid mechanics are beyond the scope of this book, the result is that the average film thickness is about

$$\delta = 25 \mu\text{m}.$$

Parallel with our earlier arguments, we now find that h_{milk} equals $[(0.60 \text{ W/m}^2\text{ }^\circ\text{C})/25 \times 10^{-6} \text{ m}]$, U is about $5000 \text{ W/m}^2\text{ }^\circ\text{C}$, and the evaporator area A is

$$A = 5 \text{ m}^2.$$

Using a centrifugal evaporator cuts the surface area required for evaporation by over thirty times.

However, this dramatically reduced area is dearly purchased. The only serious estimate that we could obtain for building a centrifuge like this was over \$50,000. This seems too expensive for most farmers. As a result, we turn to the third method for evaporation.

MEMBRANE EVAPORATION. Like the centrifugal evaporator, the membrane evaporator can sustain very thin, stable milk films during evaporation. As shown in Figure 4.4–1, the thin films are now sustained not by centrifugal force but between two thin membranes. One of the membranes is a metal foil, which transfers heat from the 64°C steam to the 60°C milk. This membrane has a heat transfer coefficient around $20,000 \text{ W/m}^2\text{ }^\circ\text{C}$.

The other membrane, which separates the 60°C milk from the 60°C steam produced by the evaporation, is the barrier for the evaporation. Interestingly, its heat transfer resistance and mass transfer resistance are predicted to be negligible under

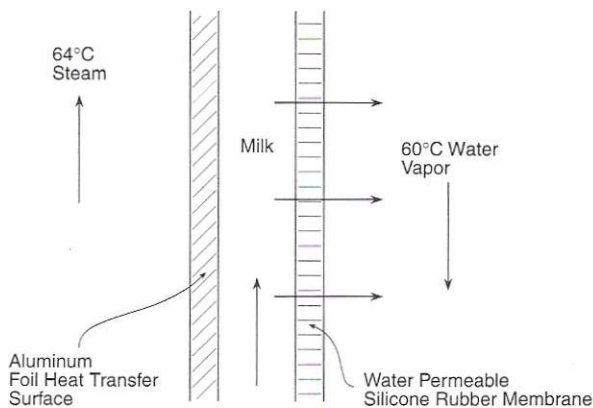


Figure 4.4–1. Membrane Evaporator. Water in warm milk evaporates across the thin membrane shown. Because the membrane is selective, volatile flavors are not lost.

TABLE 4.4–4 Risk Assessment for the Membrane Evaporator

Risk	Probability	Consequence	Risk Level	Mitigation
1. Difficult to make heat transfer membrane	0.1	0.5	0.05	Use parallel heat exchange technology
2. Difficult to make evaporation membrane	0.3	0.5	0.15	Existing data suggest, at most, required membrane area doubles
3. Cannot easily manifold the module	0.5	0.2	0.10	Can mitigate with larger steam channel
4. Evaporation flow is slow	0.5	0.2	0.10	Use larger membrane spacer in steam channel
5. Cannot sterilize effectively	0.3	0.9	0.27	Chemical cleaning preferred, but requires no dead spots

these conditions. If this is true, then the significant resistance to heat transfer must be the film of milk itself. In many membrane devices like this, the two membranes are held apart by a spacer, which fixes the thickness of the milk film. Typically, the thickness δ of this spacer is

$$\delta = 600 \mu\text{m}.$$

By the same arguments as before, h_{milk} is $[(0.60 \text{ W/m}^2 \text{ }^\circ\text{C})/6 \times 10^{-4} \text{ m}]$, U is about $900 \text{ W/m}^2 \text{ }^\circ\text{C}$, and the evaporator area A is

$$A = 23 \text{ m}^2.$$

This is one fourth the area of the falling film evaporator, but eight times the area of the centrifugal evaporator. Significantly, membrane experts agree that membrane modules like this can be built for about $\$10/\text{m}^2$, independent of the chemical structure of the membrane used. Thus we should be able to build a membrane evaporator for less than $\$1000$. Such a system is attractive commercially.

RISK ASSESSMENT. The three evaporators discussed above show a vivid contrast of advantages and disadvantages. The traditional thin film evaporator has the largest area because it operates with the thickest milk film. The centrifugal evaporator has a very small area but a very high price. The membrane evaporator has a moderate area and a very low price, but it may not work. Using the membrane evaporator is risky.

Five of the major risks of this evaporator are shown in Table 4.4–4. The first, that we have trouble making the heat transfer membrane, is unlikely because there are already foil-based heat exchangers on the market. The obvious strategy is to

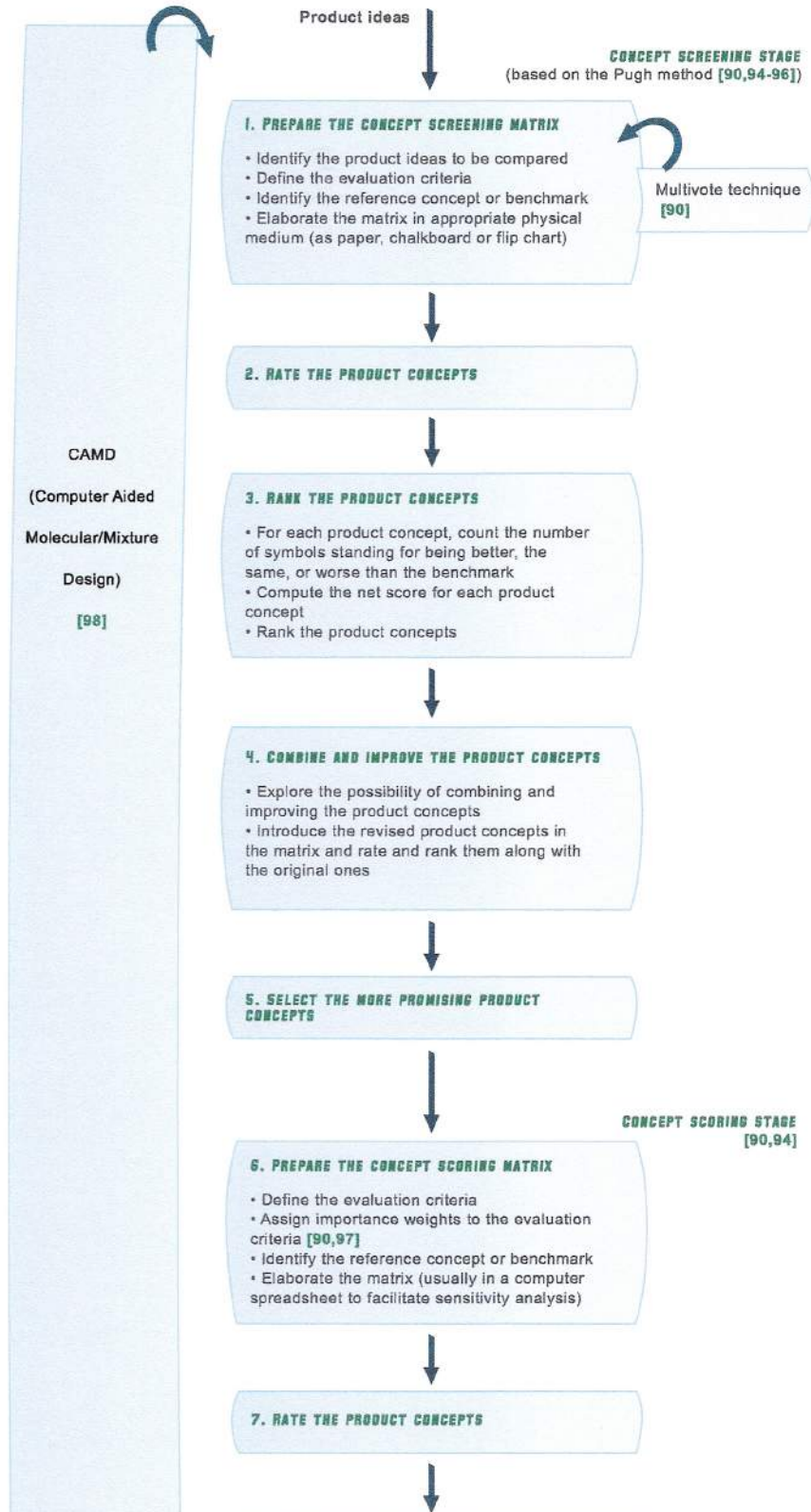
use the manufacturing procedures of these foil exchangers as a guide. The second risk, that the membrane across which evaporation occurs offers a major mass transfer resistance, is more serious. Although such trouble would be inconsistent with earlier studies of membranes with high permeability, we suspect that the membranes used in those studies may be difficult to make in the large, flat sheets needed here. However, even if the water permeability is only 20% of that reported earlier, the membrane area required increases only slightly.

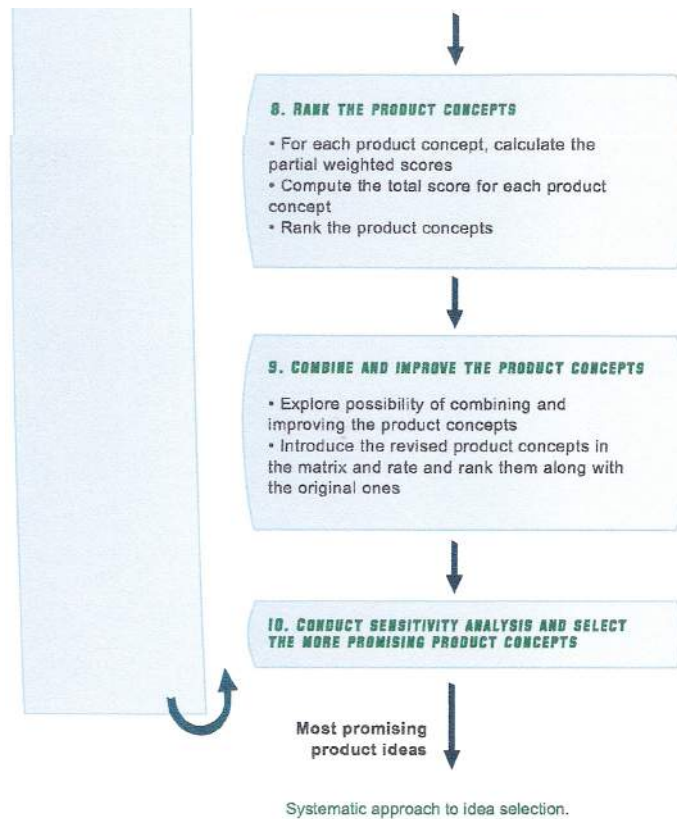
The other risks depend on the design of the evaporation module. The third risk concerns the design of the inlets and outlets, and should not be especially difficult to resolve. The fourth risk reflects the concern that the evaporated water will not easily flow out of the module. This is easily mitigated by using a larger membrane spacer in the steam channel. Sterilization of the milk channel is the most severe risk. Although the membranes may not be able to stand high temperature, most farms use chemical cleaning anyway. We must ensure that sterilization is complete, without any dead spots. Even this risk, scored as the most serious, does not seem crippling. We should build a prototype and show by experiments if this new but risky idea merits selection.

Shematski prikaz izbora ideje:

Vir: http://www.engsc.ac.uk/an/mini_projects/cpd/index.html (6.9.2011)

: summary of approaches and tools





Primeri izbora ideje za nov produkt: UV zaščitni film in Načrtovanje z vlakni ojačanega polimernega kompozita

Vir: http://www.engsc.ac.uk/an/mini_projects/cpd/index.html (6.9.2011)

Na zaključku faze izbora moramo izbrati najboljšo idejo za produkt. Naslednja faza je izdelava produkta.

Ob zaključku faze "Ideje" jedro projektnega team-a pripravi tretje fazno pisno poročilo in tretje fazno ustno predstavitev aktivnosti in rezultatov projekta. Na predstavitvi sodelujejo vodilni iz managementa organizacije. Po predstavitvi mora pasti odločitev ali se delo na projektu nadaljuje ali ne.

Tretji fazni pregled projekta je daleč najtežji in najbolj kritičen. Jedro projektnega team-a bo za razvoj produkta v naslednjih korakih potrebovalo veliko več denarja kot do tega trenutka. Zato je verjetnost, da se bo projekt zaključil v tej fazi, bistveno večja kot po fazah "Potrebe" in "Ideje".