

# A COST EFFECTIVE, ENERGY SAVING BOOSTED EVAPORATION PROCESS FOR ALUMINA REFINERIES

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## ABSTRACT

Evaporation process is a significant section in the alumina production by the Bayer Process. It consumes a large amount of thermal energy and helps to manage water balance. We introduce a novel flash boosted evaporation process that can reduce live steam consumption for evaporation purposes, by using the available waste flash vapour from the last stage of the evaporation unit. The process can economise on the consumption of live steam, as waste flash vapour injection into the patent pending Flash Boosted Thermal-Vapour Compression Multi-Effect Evaporation (FB-TVC-MEE) process is able to minimise the motive steam usage of the Thermal-Vapour Compressor (TVC). We compare this novel FB-TVC-MEE process with the conventional Thermal-Vapour Compression Multi-Effect Evaporation (TVC-MEE) process and the current Multi-Stage Flash (MSF) process in terms of the amount of saved live steam, Gain Output Ratio (*GOR*), and specific pumping power consumption.

Our result shows that 82% of the current live steam consumption can be saved, with our process having the ability to exploit all the available flashed vapour for the evaporation of feed spent liquor. The Gain Output Ratio of our design is 468% better than the current MSF system and 98% better than the conventional TVC-MEE process. With regards to the pumping power consumption, the FB-TVC-MEE process shows a 5% increase as compared to the TVC-MEE process. Importantly, at a risk discount rate of 10%, the FB-TVC-MEE process has been shown to cost the least (both capex and opex considered), auguring 57% net present cost savings compared to the standard MSF technology that consumes 40 ton per hour of live steam with a baseline capex of \$30 mil.

## 1. INTRODUCTION

In the Bayer process [1], the evaporation process is an intensive energy-consuming process that uses live steam as heat source, thereby accounting for approximately 25-30% of energy consumption per ton of alumina [2]. At the same time, it is responsible for controlling the water balance in the whole plant [2]. Therefore, any improvement to the evaporation section can decrease steam consumption, save fuel consumption in the steam plant, and will significantly reduce greenhouse gas emission and production cost.

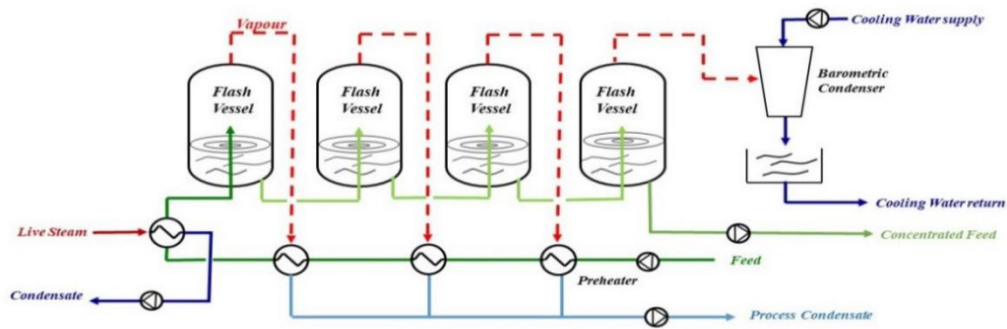
In this paper, we introduce a novel process that can ultimately be coupled with the available waste flash vapour in the last

stage of evaporation units of an alumina refinery, so as to reduce the live steam consumption as compared to both the current MSF process and the conventional TVC-MEE process.

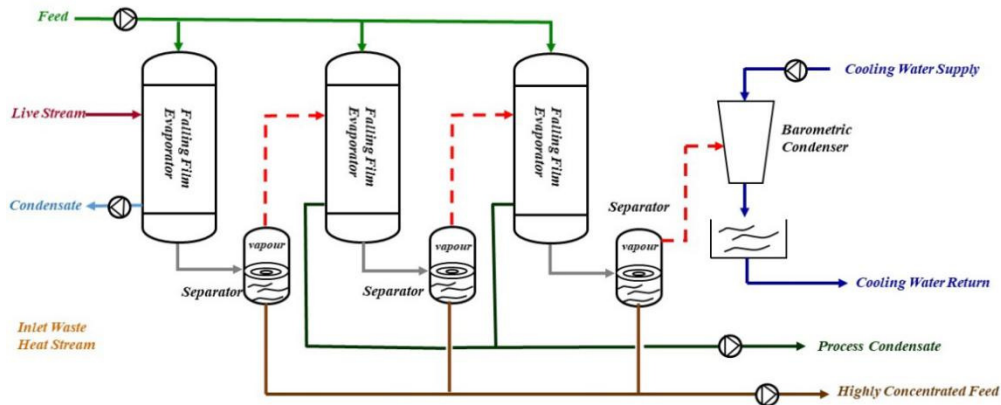
We are currently trialling the concept and the use of compact plate-type evaporator by subjecting a 1.5 m<sup>3</sup>/day (in terms of process condensate production) pilot plant to a self-contained process liquor loop.

## 2. PROCESS DESCRIPTION

Both the Multi Stage Flash process and Multi Effect Evaporation process are the conventional processes in the evaporation unit of mineral refineries (Figures 1 and 2).



**Figure 1. Schematic design of a multi-stage flash evaporation unit in alumina refineries**



**Figure 2. Schematic design of a multi-effect evaporation unit in alumina refineries**

In Figures 1 and 3, 1 kg/s live steam is considered to reconcentrate 18.45 kg/s of 19.0wt% caustic soda feed stream, for the purpose of establishing a common platform for comparison. The identified waste heat stream is from the flashed vapour from the last vessel of the evaporation unit. For benchmarking purposes, the TVC-MEE process is considered as an optimised process to harness the available waste heat source. Compared with conventional MSF process, it consumes less available live steam (35%) via a thermo-compressor to compress the available flashed vapour. Then, the remaining flashed vapour (44%) from the

flashed vapour stream is purged as a waste stream to the barometric condenser. The TVC-MEE configuration does not display any further potential to use the remaining waste stream.

In contrast, as shown in Figure 4, the FB-TVC-MEE process can effectively harvest the same flashed vapour stream. In this process, the second effect of the MEE system will receive the remaining flashed vapour (72%). This process effectively minimises the suction load of the thermo-compressor, which in turn reduce the live steam consumption to lowest amount.

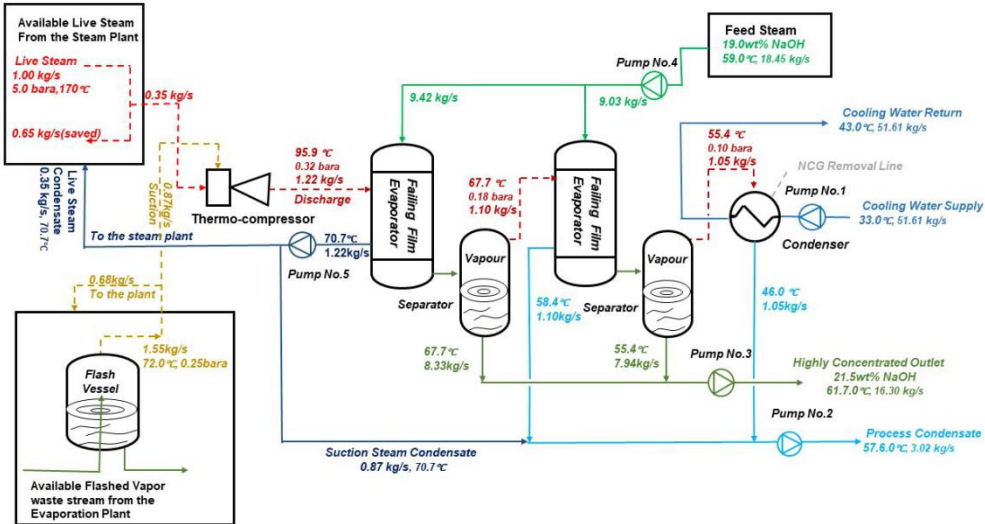


Figure 3. Schematic design of the conventional TVC-MEE process coupled with the available waste stream of the considered alumina refinery. Other than plant specifications, all figures are based on our simulations.

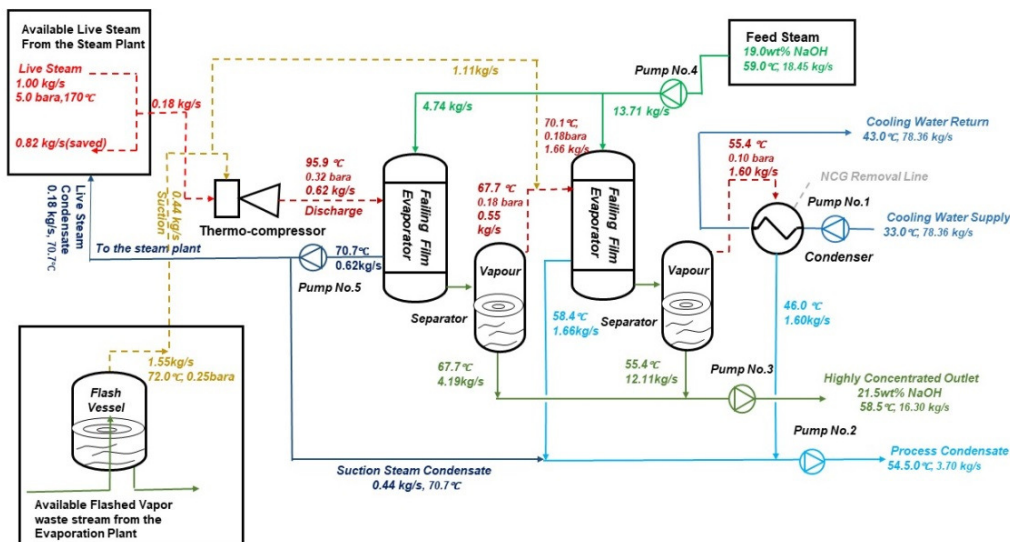


Figure 4. Schematic design of the FB-TVC-MEE process coupled with the available waste stream of the considered alumina refinery. Other than plant specifications, all figures are based on our simulations.

### 3. MATHEMATICAL SIMULATION

Tables 1 and 2 show the generic and representative specifications and boundary conditions, which stem from the laws of thermodynamics, appropriate operational and technical constraints. The mass, concentration, energy balance, condenser and thermo-compressor, are taken into consideration in our simulations and the Generalised Reduced Gradient method [3] is used to solve the equations by

imposing those boundary conditions. As a matter of illustration, the feed liquor stream has been replaced with pure caustic soda (NaOH) solution, which displays a higher Boiling Point Elevation (BPE) than the actual feed liquor stream.

**Table 1: Assumed specifications**

Live steam	Pressure (bara)	5
	Temperature (°C)	170
	Flowrate (kg/s)	1.00
Feed inlet	Concentration (wt%)	19.0
	Temperature (°C)	59.0
	Flowrate (kg/s)	18.45
Equivalent process liquor outlet (highly concentrated NaOH)	Concentration (wt%)	21.5
	Flowrate (kg/s)	16.30
Available waste heat stream(flashed vapour)	Temperature (°C)	72.0
	Pressure (bara)	0.25
	Flowrate (kg/s)	1.55
Cooling water supply	Flowrate (kg/s)	1.55
	Temperature (°C)	33.0

**Table 2: Assumptions and boundary conditions**

Recovery factor for each multi-effect evaporation effect ( $1/R$ )	12%
Temperature difference across the condenser (°C)	10.0
Minimum pressure difference for steam injection purpose (kPa)	1.0
Temperature of approach across the evaporators (°C)	3.0
Feed (NaOH) inlet/outlet concentration (wt%)	19.0/21.5
Maximum available waste flashed vapour mass flow rate (kg/s)	1.55
Maximum available live steam mass flow rate used as the motive steam in the thermo-compressor (kg/s)	1.00

The selected MSF evaporation unit is considered to consume 1kg/s live steam to reconcentrate the NaOH feed stream. As shown in Figure 3, the potential of the stream is enough to recover the load of the selected unit. The number of effects in the MEE process is two due to two main factors. The one is the high boiling point elevation (BPE) of NaOH, the other one is the temperature difference between the steam after vapour compression and the cooling water supply (Figures 3 and 4). A low recovery factor (12%) is chosen to match the current process so as to harmonise with the existing operation. However, in terms of recovery factor, the potential of an MEE process is actually much more than that.

The target of the simulation is to find the lowest possible mass flow rate that live steam required (the motive steam of the thermo-compressor). Meanwhile, it also aims to calculate the required suction flow rate of the thermo-compressor and the injected vapour mass flow rate, for the purpose of producing the same concentrate production rate compared with the selected evaporation unit.

The mass and concentration balances are written as  $k \in \{1, 2\}$ :

$$\dot{m}_{F,k} = \dot{m}_{HC,k} + \dot{m}_{V,k} \quad (1)$$

$$\dot{m}_{F,k} \cdot X_{F,k} = \dot{m}_{HC,k} \cdot X_{HC,k} \quad (2)$$

The energy balance for the first effect is expressed as

$$\begin{aligned} & \dot{m}_{HS,k} \cdot (h_{HS,1,in} - h_{f(P_d)}) \\ & = U_1 \cdot A_1 \cdot \Delta T_{lm,1} \end{aligned} \quad (3)$$

Where  $h_{f(P_d)}$  is the saturated enthalpy of the discharge steam condensate upon leaving the first effect;  $h_{HS,1,in}$  is the enthalpy of superheated steam at discharge pressure and temperature;  $h_{V,1}$  is the superheated vapour at the effect's pressure and the outlet concentrate temperature;  $h_{HC,1}$  and  $h_{F,1}$  are the enthalpies of the concentrate outlet and feed inlet streams.

The energy balance for the second effect in FB-TVC-MEE process, which receives waste flash vapour by injection, is written as

$$\begin{aligned} & \dot{m}_{HS,2} \cdot (h_{HS,2,in} - h_{f(P_1)}) \\ & = U_2 \cdot A_2 \cdot \Delta T_{lm,2} \end{aligned} \quad (4)$$

For which

$$\dot{m}_{HS,2} = \dot{m}_{V,1} + \theta \cdot \dot{m}_{V,inj} \quad (5)$$

$$h_{HS,2,in} = \frac{\dot{m}_{V,1} \cdot h_{V,1} + \theta \cdot \dot{m}_{V,inj} \cdot h_{V,inj}}{\dot{m}_{V,1} + \theta \cdot \dot{m}_{V,inj}} \quad (6)$$

Where  $\theta$  is used to distinguish TVC-MEE from the FB-TVC-MEE process, ( $\theta = 0$ ) for TVC-MEE and ( $\theta = 1$ ) for FB-TVC-MEE.

The energy balance for the condenser is shown as:

$$\begin{aligned} \dot{m}_{V,2} \cdot (h_{V,2} - h_{f(P_2)}) &= \dot{m}_C \cdot (h_{C,out} - h_{C,in}) \\ &= U_{cond} \cdot A_{cond} \cdot \Delta T_{lm,cond} \end{aligned} \quad (7)$$

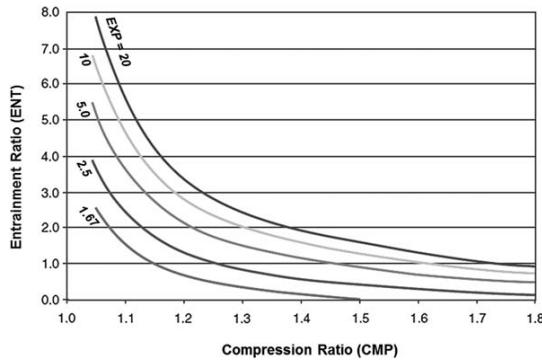
In our simulation, 3°C is assumed to be the temperature difference between the concentrate outlet boiling temperature and the heat source condensation temperature.

For the thermo-compressor, the following two equations are used to calculate the required motive and suction mass flow rates.

$$\dot{m}_m = \dot{m}_s / ENT \quad (8)$$

where  $ENT$  is the entrainment ratio to be found from Figure 5 [4] and

$$\dot{m}_d = \dot{m}_s + \dot{m}_m \quad (9)$$



**Figure 5. Thermo-compressor entrainment chart. Adapted from Reference [4].**

The discharge enthalpy and temperature shows in the following energy balance equation, which is expressed as

$$h_d = \frac{\dot{m}_m \cdot h_m + \dot{m}_s \cdot h_s}{\dot{m}_s + \dot{m}_m} \quad (10)$$

where  $h_m = h_{g(P_m, T_m)}$  and  $h_s = h_{g(P_s, T_s)}$ . The discharge temperature  $T_d = f(h_d, P_d)$ , which is a function of the discharge pressure and enthalpy that can obtain from steam property routine. This temperature is indicated as the degree of superheating

which enjoins extra heat exchanger area to desuperheating.

The overall production of wash water is the sum total of the condensate flow rate from each effect in the MEE process:

$$\dot{M}_{D,total} = \sum_{k=1}^2 \dot{m}_{v,k} + \theta \cdot \dot{m}_{V,inj} + \dot{m}_s \quad (11)$$

$$\dot{M}_{HC,total} = \sum_{k=1}^2 \dot{m}_{HC,k} \quad (12)$$

We use the Generalised Reduced Gradient (GRG) method to solve equations 1-12, aiming to find the lowest motive steam flow rate to produce the same concentrate flow rate as the original process (the MSF process) by imposing the boundary conditions for both the conventional TVC-MEE and FB-TVC-MEE processes. For the properties of steam and vapour that are needed in calculations in above equations 1-12, the REFPROP package (REFerence fluid PROPERTIES) as developed by the National Institute of Standards and Technology [5] has been used. The properties of NaOH are obtained from [6-11]. For the simulation of the MEE process, extensive relevant and detailed data can be found in the References [12-13].

## 4. RESULTS AND DISCUSSION

### 4.1 Steam consumption

Based on the above assumptions and methods, Tables 3 and 4 compare the amount of steam saving and recovered waste flashed vapour stream in all three processes.

For the TVC-MEE process, as there is no steam injection into the second effect, only around 56% waste flashed vapour stream is recovered and the remaining 44% is unused (0.68kg/s out of 1.55kg/s). Obviously, the FB-TVC-MEE process is superior with 82% saving of the available live steam. Concomitantly, the entire waste flashed vapour stream is fully consumed in the FB-TVC-MEE process, such that 28% of which is subjected to thermal compression while the balance is summarily injected into the second effect.

**Table 3: Available live steam, live steam consumption and recovered flashed vapour**

	MSF	TVC-MEE	FB-TVC-MEE
Available live steam (for MSF) (kg/s)	1.00	1.00	1.00
Live steam consumption (kg/s)	1.00	0.35	0.18
Available waste flashed vapour (kg/s)	1.55	1.55	1.55
Recovered waste flashed vapour stream (kg/s)	0	0.87	1.55

MSF, multi-stage flash; TVC-MEE, thermal vapour compression; FB-TVC-MEE, flash-booster thermal vapour compression multi-effect evaporation

**Table 4: Available Live steam and Percentage Recovery of Waste Flashed Vapour Stream**

	TVC-MEE	FB-TVC-MEE
Available Live Steam Saving Percentage	65%	82%
Percentage Recovery of Flashed Vapour	56%	100%

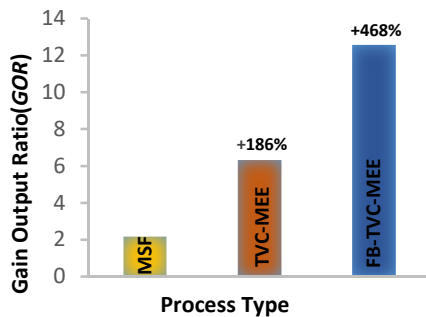
#### 4.2 Gain Output Ratio

The *GOR*, as a key factor, is defined as the amount of favourable production by one unit of consumed live steam. The *GOR* is calculated based on Equation 13.

$$GOR = \frac{\dot{m}_p}{\dot{m}_m} \quad (13)$$

where  $\dot{m}_m$  is the motive steam flowrate, and  $\dot{m}_p$  is the total produced process condensate excluding the injected vapour from the waste flash vapour stream, as the latter has always been available.

As shown in Figure 5, the *GOR* of FB-TVC-MEE is the highest, which is nearly 5.7 times more than the MSF process and 98% better than the TVC-MEE process. Obviously, it can utilise the live steam more effectively compared to the other two processes.



**Figure 5. Gain Output Ratio (*GOR*) of the current MSF, TVC-MEE, FB-TVC-MEE processes**

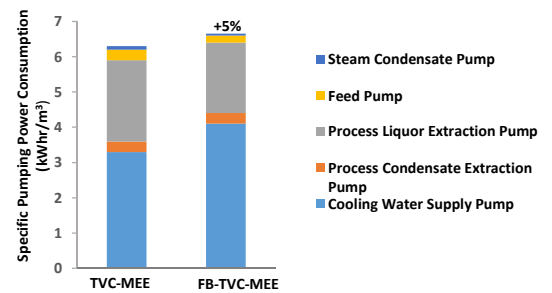
#### 4.3 Pumping Power Consumption

As indicated in Figures 3 and 4, there are five essential pumps which are used to

supply the cooling water, to extract the process condensate and the concentrate from the MEE effects, to feed the effects and extract steam condensate from the first effect respectively. The pumping power is calculated according to following Equation 14.

$$Pumping\ power(kW) = \left( \frac{\Delta P \cdot \dot{V}}{\eta} \right) \quad (14)$$

where  $\Delta P$ ,  $\dot{V}$  and  $\eta$  are the total head (kPa), volumetric flow rate ( $m^3/s$ ), and the overall efficiency of the pump, respectively. The specific pumping power of FB-TVC-MEE is compared with TVC-MEE as in Figure 6. It shows the cooling water supply pump (pump no. 1) being the main unit. As to the process condensate production rate, the specific pumping power in FB-TVC-MEE is only 5% more than that of TVC-MEE, on account of the high flashed vapour recovery.



**Figure 6. Specific pumping powers for the two proposed evaporation processes.**

## 5. SPECIFIC CAPITAL COST

As a key parameter, the capital cost of the conventional thermal desalination plants can be estimated based on the GWI/IDA database [14]. The conservative cost (the capacity under 10,000 m<sup>3</sup>/day) can be expressed by the following function [15]:

$$\Psi_{D_t} = 3054 \times D_t^{0.9751} \quad (15)$$

where  $D_t$  is the total distillate production rate of the plant in (m<sup>3</sup>/day). For the TVC-MEE process, it is used to calculate the capital cost as a function of process condensate (distillate) production rate. But as for the FB-TVC-MEE, the capital cost should be analysed by considering its condensate capacity of the FB-TVC-MEE and the injected flashed vapour flow rate to the second effect.

As the vapour is injected from the unused flashed vapour stream, only condensation takes place in the MEE section. It is assumed that similar overall heat transfer coefficients apply to both evaporation process and condensation process [15], which means only half of the typical heat transfer area is needed to process the additional vapour injection. Then, it can be translated to a 50% discount of the previous introduced cost breakdown for the evaporator (50% of 40% for the cost of evaporator). Therefore, the abovementioned factor is applied to calculate the capital cost differential between an MEE plant with a process condensate production capacity of an FB-TVC-MEE plant and an MEE plant with the process condensate production capacity of an FB-TVC-MEE plant less the total vapour injection rate from the flashed vapour unused stream, as written in following Equation 16 [14-15].

$$CC_{(FB-TVC-MEE)} = \Psi_{(D_{t(FB-TVC-MEE)} - D_{inj})} + \left[ 0.2 \cdot \left( \frac{\Psi_{D_{t(FB-TVC-MEE)}}}{-\Psi_{(D_{t(FB-TVC-MEE)} - D_{inj})}} \right) \right] \quad (16)$$

where  $D_{t(FB-TVC-MEE)}$  is the total process condensate (distillate) flow rate (m<sup>3</sup>/day) of the FB-TVC-MEE and  $D_{inj}$  is the injected flashed vapour flow rate (m<sup>3</sup>/day) into the second effect of the MEE section.

The total capital cost equation for FB-TVC-MEE is written as:

$$TCC(\text{US\$}) = (0.4 \cdot \gamma + 0.6) \cdot (CC) \quad (17)$$

and the specific capital cost can be written by Equation 18

$$SCC(\text{US\$}/(\text{m}^3/\text{day})) = TCC/D_t \quad (18)$$

where  $D_t$  is the process condensate production rate (m<sup>3</sup>/day),  $\gamma$  is the overall area coefficient factor.

According to the above equations, the total and specific capital costs can be calculated. Due to the higher recovery of the waste flashed vapour stream, the specific capital cost of the FB-TVC-MEE is around 11% less than that of the TVC-MEE process.

## 6. NET PRESENT COST SAVINGS

The net present costs ( $NPC$ ) can be calculated by the following equation:

$$NPC = \sum_{t=1}^n \frac{C_t}{(1+r)^t} + C_0 \quad (19)$$

where  $C_t$  is the opex expense during the period  $t$ ,  $C_0$  is the initial investment cost,  $r$  and  $t$  are the risk discount rate and number of time periods, respectively. In this paper, the opex expense is taken to be the cost of live steam consumption, and the baseline initial investment cost for the MSF plant is considered to be \$30 million, which consumes 40 ton/hr of live steam, and the plant life ( $n$ ) and risk discount rate are assumed to be 30 years and 10%, respectively. The latter reflects the risk of new technologies. The cost of steam is considered to be \$10 per ton.

Accordingly, for MSF and TVC-MEE, the net present costs ( $NPC$ ) are \$61 and \$35 million over a span of 30 years, respectively. Namely the adoption of TVC-MEE could save 44% of  $NPC$ . For the FB-TVC-MEE process, it is \$27 million, thereby saving 57% of  $NPC$  as compared with MSF.

## 7. CONCLUSIONS

A novel flash boosted thermal vapour compression multi-effect evaporation (FB-TVC-MEE) process has been developed to fully recover the available waste flashed vapour streams in an alumina refinery plant. This novel process can save approximately 82% of the selected evaporation unit's available live steam and the thermal performance is 468% better



than the current system and 98% better than the optimised thermal vapour compression multi-effect evaporation (TVC-MEE) process. Compared with the TVC-MEE process, the FB-TVC-MEE shows a 5% increase in terms of the specific power consumption and an 11% decrease in terms of the overall specific capital cost. Importantly, considering a risk discount rate of 10%, the net present costs (*NPC*) incurred by the TVC-MEE process over 30 years is \$35 million, while that of the FB-TVC-MEE process is \$27 million, representing net present cost savings of 44% and 57%, respectively, as compared to the standard MSF technology.

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## 9. SUBSCRIPTS

1	First effect
2	Second effect
<i>C</i>	Coolant (Cooling water supply)
<i>calc.</i>	Calculated
<i>cond</i>	Condenser
<i>d</i>	Discharge steam
<i>D<sub>inj</sub></i>	Injected vapor flowrate
<i>F</i>	Feed
<i>V</i>	Vapour
<i>HC</i>	Highly concentrated process liquor
<i>HS</i>	Heat source (for effects), hot side (for the condenser)
<i>FB-TVC-MEE</i>	Flash Boosted TVC-MEE
<i>in</i>	Inlet
<i>inj</i>	Injected
<i>k</i>	MEE effect number
<i>lm</i>	Log mean
<i>m</i>	Motive steam
<i>out</i>	Outlet
<i>p</i>	Process condensate
<i>P<sub>1</sub></i>	First effect pressure
<i>P<sub>2</sub></i>	Second effect pressure
<i>P<sub>d</sub></i>	Discharge pressure
<i>s</i>	Suction steam
<i>sat</i>	Saturated temperature



## 10. NOMENCLATURE

$A$	Evaporator area (m <sup>2</sup> )
$D_t$	Total process condensate production rate (m <sup>3</sup> /day)
$ENT$	Entrainment ratio
$TCC$	Total capital cost (US\$)
$SCC$	Specific capital cost (US\$·day/m <sup>3</sup> )
$CC$	Capital cost (US\$)
$NPC$	Net present costs (US\$)
$GOR$	Gain output ratio
$U$	Overall heat transfer coefficient (kW/m <sup>2</sup> ·K)
$T$	Temperature (°C)
$\Delta T$	Temperature difference (°C)
$g$	Acceleration of gravity (m/s <sup>2</sup> )
$h$	Enthalpy (kJ/kg)
$h_f$	Enthalpy of saturated liquid (kJ/kg)
$\dot{M}_{D,total}$	Total process condensate mass flow rate (kg/s)
$\dot{M}_{HC,total}$	Total highly concentrated liquor mass flow rate (kg/s)
$h_g$	Enthalpy of steam (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
$n$	Plant life (year)
$P$	Pressure (bar)
$\Delta P$	Pressure difference (kPa)
$r$	Risk discount rate
$R$	Feed to vapour ratio
$X$	Concentration (wt%)
$\eta$	Overall pump efficiency
$\gamma$	The overall area coefficient factor
$C_t$	Opex expense (US\$)
$C_0$	Initial investment cost (US\$)
$\theta$	Flag distinguishing FB-TVC-MEE from TVC-MEE
$\Psi$	Cost function (US\$)