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Heat Pump for Energy Efficient Sugarcane Juice Freeze Pre-Concentration

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ABSTRACT

Freeze Pre-Concentration System, FPCS, with low lift reversible heat pump is designed for selective freezing of water from sugarcane juice. Two identical vented double wall tube-and-tube heat exchangers are used, to freeze water in the evaporator and melt ice in the condenser, alternately. They are sized based on the cooling capacity offered by compressor, ice growth rate and velocity of juice inside the tube to reduce inclusion. Low lift heat pump is designed to operate at -8ºC evaporator and 3ºC condenser saturation temperatures. Since, the condenser duty is higher than evaporator duty, excess heat duty in the form of superheat is utilized to heat pre-concentrated juice. Raw juice is precooled in a three stream Tube-and-Tube Heat Exchanger, TT_HE. Raw juice is precooled using cool concentrated juice and separated water. Freeze pre-concentration of sugarcane juice from 20°Brix to 40°Brix using a low lift reversible heat pump saves bagasse during initial 63% water removal. Water is removed through the freezing process requires 335 kJ/kg heat removal, which is equivalent to 15% of heat addition during evaporation at atmospheric pressure in open pan in jaggery making.

Investigations on selection of refrigerant R744, R290 and R22 for FPCS are presented. R290 is identified as preferred refrigerant. It is natural refrigerant, no ODP and significantly lower operating pressures compared to R744. R290 charge of 360 g for 1.5 TR compressor based system is managed by using small diameter refrigerant side tubes. It address safety related issues for modular small capacity systems. Superheat temperature of compressed refrigerant is 9ºC for R290. It allows to size the identical LHEs with R290 as a refrigerant. Flashing of refrigerant in evaporator is 7% for R290 and 10% R744. Generally, R744 is preferred when high temperature heating is required. But, high superheat at compressor outlet and increased flashing at evaporator inlet reduces the performance of R744 system making it less preferred as compared to R290 and R22. Theoretical cycle COP_c calculated for R290 based reversible heat pump works out to be 20, with compressor isentropic efficiency of 70%. Overall system COP_c is in the range of 10 to 13 after accounting for losses like cycling of thermal mass, heat gain from ambient, variation in freezing point depression and ice layer thickness. System Carnot efficiency is in the range of 41 to 54%. Power required for 1.5 TR FPCS is 0.4 to 0.6 kW_e. Different juice side tube diameters are considered to find the optimal size, after accounting for effect of thermal mass of heat exchanger, heat pump switching time and inclusion on the energy consumption per unit water separated. Achievable energy consumption is in the range of 9 to 12 kWh_e/m^3 of water separated.

Keywords: Low lift reversible heat pump, Freeze Pre-concentration System, thermal mass, COP, inclusion.

1. INTRODUCTION

Conventional process of jaggery making uses the heat of bagasse to evaporate water in open pan process. It consumes entire bagasse and sometime additional fuel is required. Flue gas side pan surface is exposed to very high temperature, about 500 to 600ºC. It caramelizes the sugar available in the raw juice. It gives dark brown colour to jaggery, which has less market value than golden yellow colour jaggery. Reducing pan surface temperature enhances the jaggery colour. This can be achieved using Freeze Pre-concentration System with Heat Pump. This also relives operators from strenuous and harsh operating conditions in front of open pans. It saves about 63% bagasse and can be used as manure after composting. Freeze pre-concentration using low lift heat pump separates water selectively from raw juice at low freezing temperature. It ensures the low temperature of raw juice during initial phase of water removal. Temperature lift of heat pump is 11ºC with -8ºC evaporator and 3ºC condenser temperature. R290 is used in heat pump. It has no ODP and ~20 GWP. It also gives low compressor outlet temperature as compare to R744 and R22. Cooling coefficient of performance is 20 using R290 as refrigerant. In this paper, investigations on refrigerant selection for low reversible lift heat pump for FPCS and effect of thermal mass on tube selection for LHE are presented.

1.1 Conventional jaggery making process

In conventional jaggery making process, harvested sugarcane from field is stored near the crushing area. Raw juice is extracted by horizontal roller crusher operated using electric motor or diesel engine. Conventional jaggery making process with typical number of quantity is shown in Figure 1.

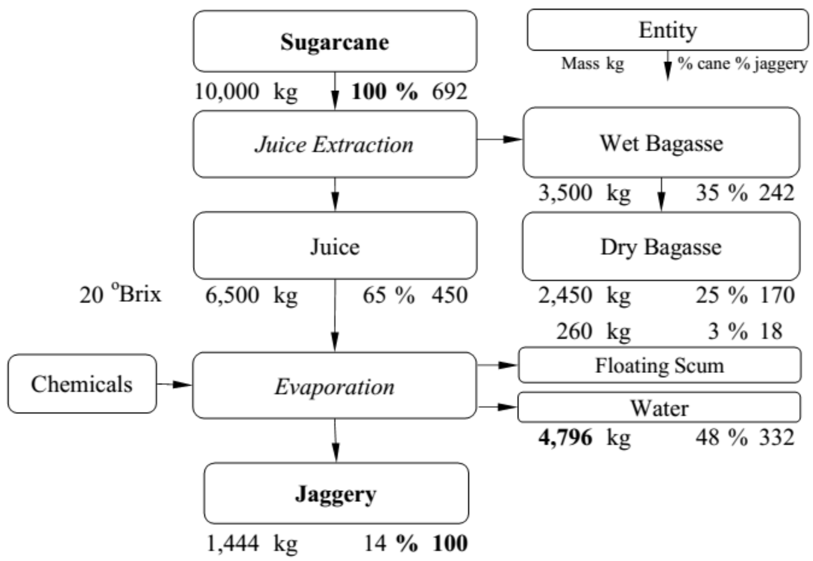


Figure 1: Conventional Jaggery Making (Rane and Uphade, 2015)

Typical extraction efficiency ranges from 60 to 70%. Residue of juice extraction is bagasse. It contains about 45 to 55% moisture. It is sun dried up to 15 to 25% by spreading in open space. Raw juice is filtered to remove suspended fine bagasse particles and pumped to settling cum storage tank. As the earlier batch finishes, filtered juice is preheated to 70 to 85ºC in pan and first scum is removed. Clarificants like milk of lime, phosphoric acid, hydros powder, mucilage of lady's finger are added to improve clarification and quality of jaggery. Frothing and bubbling of juice is reduced by continuous stirring using manual scrapping at bottom of pan or rotating horizontal rod mechanism. Second scum is removed as concentration progresses. Total scum quantity ranges from 1.5 to 4% of juice. Continuous stirring helps to prevent frothing, spillage of juice from pan and caramelization of sugar (Kulharni, 1996) by reducing hot spot formation as turbulence in juice instead of pool heating. Viscosity of syrup is tested by skilled person. Syrup from pan is poured in cooling and crystallizing pot. This cooled syrup is poured in moulds covers with wet cotton cloth or gunny bags. It facilitates easy removal of solid jaggery from moulds. This conventional jaggery making process may slightly vary from region to region. Quality of jaggery depends on variety of sugarcane, its cultivation, farming, practices applied in usage of water and fertilizer, boiling practices like use of clarificants, furnace firing practices, pan and furnace specifications.

1.2 Limitation of conventional jaggery making process

Number of open pan/s used for concentrating juice depends on severity of bagasse use. Some cane varieties are sugar rich while some are fibre rich. Single pan jaggery making with sugarcane having low fibre and high sugar content may require additional fuel other than bagasse. This issue was addressed by increasing number of pans for preheating and concentration. Two, three and four pan furnaces are reported in literature. It shows that furnace heat utilization efficiency increases with number of pans. It increases the initial investment and operating cost by increased manpower. Quality of jaggery is still being questioned, as chemical clarificants are used to enhance colour of juice and hence colour of jaggery. Organic sugarcane cultivation and crushing same sugarcane for organic jaggery making using only vegetative clarificant showing huge potential in Indian market as well as for export. This huge opportunity can be met by continuous and automated operation of small jaggery units. These issues are addressed by Energy Efficient Freeze Pre-concentration of Sugarcane Juice using a Reversible Heat Pump.

2. FREEZE CONCENTRATION PROCESS

Water is removed in the form of ice from sugarcane juice by selective freezing. This process of water removal is shown by freezing curve in sucrose-water phase equilibrium diagram, Figure 2. Sugarcane juice at room temperature and 20°Brix (Shiralkar *et al.*, 2014) is subcooled from point 'a' to 'b'. Solidification of water commences, at point 'b', at -1.5°C, simultaneously concentration of remaining juice increases, during process 'b' to 'c'. Due to dissolved sucrose in water, water gets freeze out at -1.5°C instead of 0°C if the water is pure. This drop in freezing temperature of water in juice is called as freezing point depression. Concentration of outlet juice depends on quantity of water frozen out and it is limited by eutectic temperature, which is -13.9°C at 63°Brix. Beyond this point, the whole juice gets solidified and aim of concentration of juice cannot be achieved.

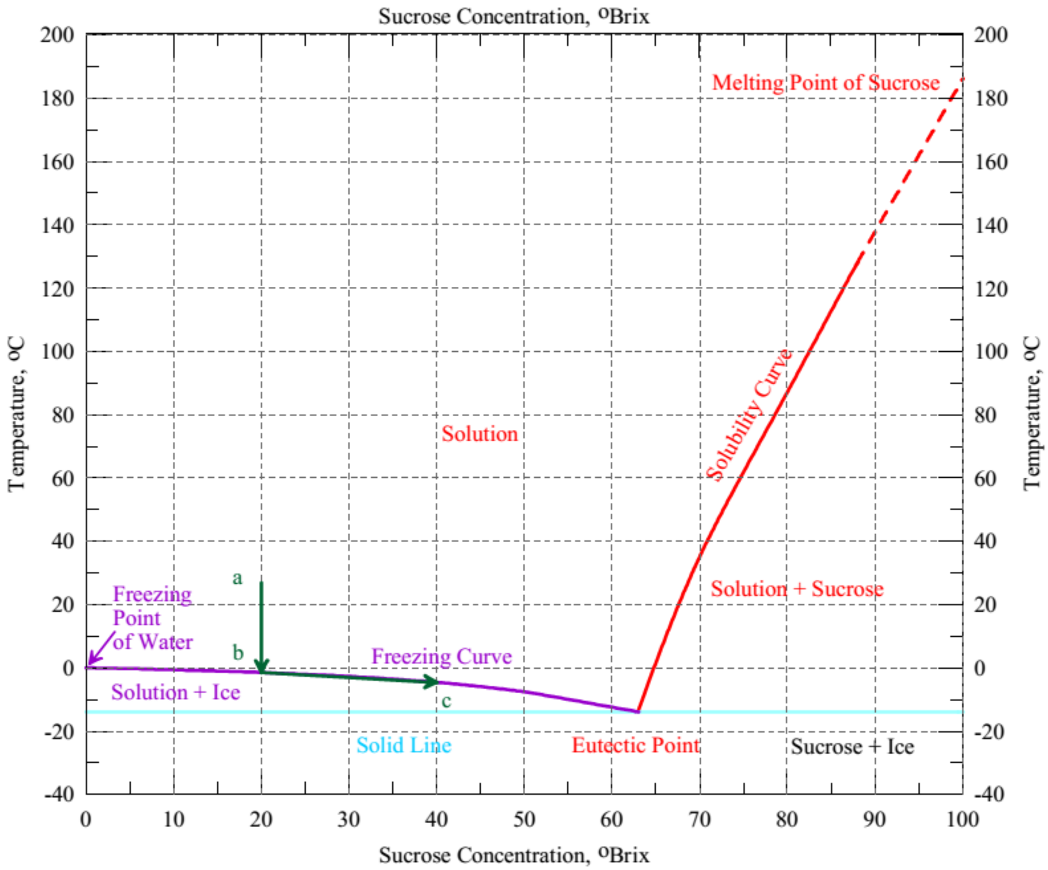


Figure 2: Sucrose-Water Phase Equilibrium Diagram (Mathlouthi and Reiser, 1995)

Process a to b: subcooling of solution, temperature reduces from 30°C to -1.5°C

Process b to c: freezing of water, temperature reduces from -1.5°C to -4.6°C for 20 to 40°Brix of solution

Ice formed by concentrating 1 kg solution from 20 to 40°Brix is estimated by equation (1), using mass and concentration balance,

$$m_{ice} = m_{rj}\left(1 - \frac{c_{rj}}{c_{cj}}\right) \tag{1}$$

This shows that from 1 kg solution at 20°Brix, out of 800 g of water, 500 g water is removed in the form of ice, which is 63% of total water in the initial solution.

Freezing of water inside the tube is reported by Miyawaki *et al.*, (2005), for coffee extract, tomato juice and sucrose solution. Solution is recirculated in closed loop arrangement. Water freezes layer by layer inside the circular tubes, subcooled from outside and after sufficient ice deposition, the whole system is dismantled to remove ice from the tubes. Sugar solution is concentrated from 8.9°Brix to 20.7°Brix in 90 min with 5.49 mm/h ice growth rate, inclusion is 0.65°Brix. Second sample of solution is concentrated from 41.4°Brix to 54.8°brix in 130 min with 3.04 mm/h ice growth rate, inclusion is 18.7°Brix.

Auleda *et al.*, (2011) developed a calculation methodology to design a multi-plate freeze concentrator for fruit juice concentration. Juice flows over the vertical parallel plates under gravity. Rane and Jabade (2005) proposed freeze concentration of sugarcane juice using a heat pump and have shown that concentration of juice from 20 to 40°Brix saves about 77% bagasse with improvement in quality. Specific power requirement is 17.2 kWh_e/m^3 water removal. Rane and Padiya, (2010) showed two stage heat pump with external condenser for freeze concentration of seawater desalination requires 9 to 11 kWh_e/m^3 water at COP_c 8 to 12. Improved freeze pre-concentration system is investigated and compared for sugar inclusion, energy consumption and system cost.

3. FREEZE PRE-CONCENTRATION SYSTEM

Schematic of Freeze Pre-concentration System for sugarcane juice pre-concentration from 20°Brix to 40°Brix is shown in Figure 3. This system consists of heat exchangers namely Liquid-Liquid Heat Exchanger, LL_HE, two Latent Heat Exchangers, LHE and Concentrated Juice Heat Exchanger, CJ_HE.

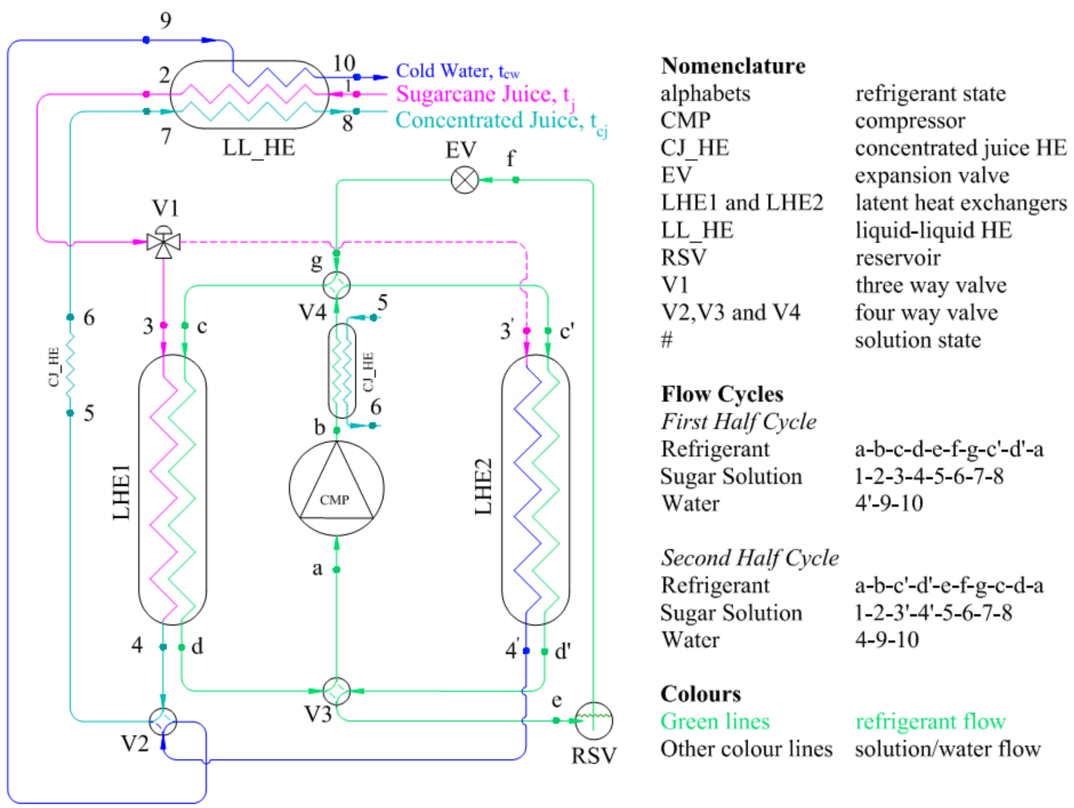


Figure 3: Heat Pump based Freeze Pre-concentration of Sugarcane Juice

LL_HE precools the sugarcane juice using streams of concentrated juice coming from CJ_HE and cold water coming from LHE during each half cycle. One LHE is used freezing of water from juice flow and another for melting of ice. They are operated alternately as evaporator and condenser. CJ_HE recovers the superheat of refrigerant for heating of concentrated juice coming from evaporator.

This system consists of 1 three way valve, V1, for directing juice flow to LHE, working as evaporator and 3 four way valves, V2, V3 and V4. Valve, V2, for directing concentrated juice flow coming from evaporator to LL_HE and two valves, V3 and V4 for directing refrigerant flow in heat pump circuit. R290 compressor with 1.5 TR is selected to investigate effect of thermal mass of LHE. SS304 circular tube OD 9.52, 1 mm thick, 6 m long tubes in series are used in LHE with Tube-Tube type Heat Exchanger.

Process of cooling and heating in LHE is shown in Table 1.

Table 1: Process of Cooling or Heating in LHE during Each Half Cycle

LHE	Works / In/Out	First Half Cycle Process	Second Half Cycle Process
LHE1	Work as	**Evaporator**	**Condenser**
	Inlet	Subcooling of raw juice, freezing of water, concentration of juice, subcooling of ice	Sensible and latent heating of ice Melting of ice
	Outlet	Concentrated juice	Water
LHE2	Work as	**Condenser**	**Evaporator**
	Inlet	Sensible and latent heating of ice Melting of ice	Subcooling of raw juice, freezing of water, concentration of juice, subcooling of ice
	Outlet	Water	Concentrated juice

3.1 Working principle

Fresh sugarcane juice at room temperature about 27ºC enters in the evaporator, LHE1, through LL_HE where it gets pre-cooled to -1.5ºC before entering into the evaporator, LHE1. At freezing temperature of juice, which is -1.5ºC, ice layer starts to build up inside the tube. It will start to build up pressure drop, as a result pressure drop across the evaporator will increase. This reduces the evaporator temperature, as ice thickness has low thermal conductance. Expected thickness of formed ice in the system is 1 to 3 mm. Simultaneously, in condenser, LHE2, ice gets heated in two steps, comprising sensible heating from -4.6ºC to 0ºC, followed by latent heating, at 0ºC. At certain low evaporator pressure, all three way and four way valves are operated for the second a half cycle of the system. During second half cycle, LHE1 acts as condenser and LHE2 will acts as evaporator.

Refrigerant circuit removes heat from the evaporator and rejects it into condenser. Sugarcane juice circuit gives heat in evaporator and ice receives back in condenser. Compressed refrigerant enters into the CJ_HE and dissipates superheat for heating concentrated juice coming out from evaporator, LHE1, and then used to precool incoming juice. Refrigerant vapor are further cooled by melting ice in condenser, LHE2. Liquid refrigerant from LHE2 is directed to four way valve, V3 and expanded into the evaporator, LHE1, through expansion valve. It receives heat from precooled juice. Saturated vapor of refrigerant are sucked by compressor and half cycle repeats after switching of valve back to the first half cycle.

3.2 Selection of refrigerant

Refrigerant R744, R290 and R22 are compared to use for FPCS. Evaporator and condenser pressure are higher for R744. Density of vapor at inlet of compressor is highest as compare to other selected refrigerants. It allows to build the system with small diameter tubes. High ratio of specific heat leads to higher compressor exit temperature of refrigerant. High superheat increases irreversibility and reduces the COP. Ammonia is toxic as well as flammable. R22 have high GWP and it will be phase out in 2020 in India. R134a is also having high GWP. R600 has 6% less latent of vaporization than R290. Compressors are not readily available in Indian market. Hence, it is less preferred. R407C and R410A are zeotropic mixtures. They have high GWP. Latent heat of vaporization is about 7% less than R290.

R290 is identified as preferred refrigerant as it is natural refrigerant, no ODP and significantly lower operating pressures compared to R744. R290 charge of 360 g for 1.5 TR compressor based system is managed by using small diameter refrigerant side tubes. It address safety related issues for modular small capacity systems. Superheat temperature of compressed refrigerant is 9ºC for R290. It allows to size the identical LHEs with R290 as a refrigerant. Flashing of refrigerant in evaporator is 7% for R290 and 10% R744. Generally, R744 is preferred when high temperature heating is required. But, high superheat at compressor outlet and increased flashing at evaporator inlet reduces the performance of R744 system making it less preferred as compared to R290 and R22.

Table 2: Refrigerants for Heat Pump based FPCS, Their Properties and Major Issues

	Refrigerant	ODP	GWP_{100}	p			t	h_{lat}	$\rho_{v.cmp.i}$	γ_v	Major Issues
				at -8°C	*at 3°C*	*critical*		at -8°C	at -8°C	at -8°C	
				bar	bar	bar	°C	kJ/kg	kg/m³		
R744	Carbon Dioxide	0	1	28.0	37.7	73.8	31.0	254	75.8	1.90	High pr, γ_v
R717	Ammonia	0	< 1	3.2	4.8	113.3	132.3	1291	2.6	1.38	Toxic and flammable
R290	Propane	0	~20	3.7	5.2	42.5	96.7	386	8.1	1.21	Flammable
R22	Dichlorofluro-methane	0.04	1790	3.8	5.5	50.0	96.1	211	16.4	1.28	High GWP
R134a	Tetrafluoro-ethane	0	1370	2.2	3.3	40.6	101.1	205	10.3	1.17	High GWP
R600	Butane	0	~20	1.2	1.7	38.0	152.0	362	3.0	1.13	Flammable
R407C	R32/125/134a (23/25/52)	0	1700	4.1	6.1	46.3	86.0	222	14.7	1.22	High GWP
R410A	R32/125 (50/50)	0	2100	6.0	8.7	49.0	71.4	231	23.0	1.34	High GWP

(Data source: ASHRAE HBF 2013)

3.3 Heat exchangers

There are four Tube-Tube Heat Exchangers in FPCS, LL_HE, two LHEs and CJ_HE. Velocity of juice increases as compare to the Tube-in-Tube Heat Exchangers. This increase in velocity reduces the inclusion of sugar in separated ice (Chen *et al*., 2014). Ice growth rate reduces, if it is formed on outer surface of refrigerant tube. Velocity of juice in annulus area reduces, which increases loss of sugar in separated water. TT_HE prevents any accidental mixing of refrigerant into the juice. Mass of material required for juice side tube in TT_HE also reduces as smaller diameter tube is selected. It reduces the thermal cycling loss during reversal of each half cycle. Raw juice is pre-cooled using cold water and concentrated juice streams. Evaporator and condenser are identical. Evaporator becomes condenser and condenser in earlier half cycle becomes evaporator during next cycle. Excess heat of compressor is utilized for heating of concentrated juice.

3.4 Effect of LHE thermal mass

Commonly available SS304 tubes, OD 6.35, 9.52, 12.7, 19.05 and 25.4 mm are selected for comparison of thermal masses and other parameters. Typically ice formed inside the tube during each half cycle is two-third of internal volume of tube. Ice thickness is calculated based on ice volume. Ratio of latent heat of ice formed to the total of latent heat of ice and enthalpy due to thermal mass of tube gives cooling effect utilized for ice formation. It increases as the tube diameter increases. It is 89% for OD 9.52 mm tube. If smaller tube with OD 6.35 mm is selected then, cooling effect lost due to thermal mass increases to 20%. As well as, for same tube length, number of cycle switching increases and it increases loss due to thermal mass of LHE and washing loss.

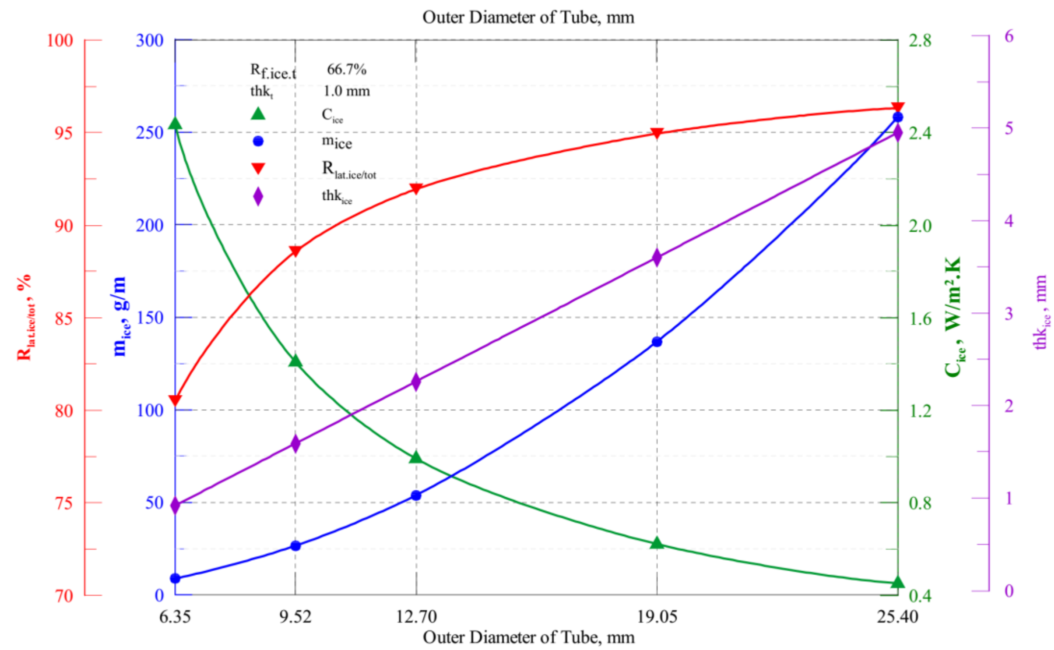


Figure 4: Thermal Mass and Other Parameters for Different Tube Sizes

Smaller diameter tube gives higher velocity. High velocity of solution reduces the Average Distribution Coefficient, ADC. Low ADC reduces the inclusion of sugar in the separated ice (Chen *et al.*, 2014). Inclusion of sugar in separated water is 32%. Thermal conductivity of ice is 2.24 W/m.K. Conductance through ice layer decreases as the ice thickness increases. It reduces overall heat transfer coefficient. Conductance of 1.6 mm thick ice is 1.4 kW/m^2.K for OD 9.52 tube. Mass of ice separated from raw juice is 27 g/m length of tube. Tube with OD 9.52 mm is selected for LHEs based on conductance of ice layer and thermal mass of tube.

3.5 Calculations

Mass flow rate of raw juice, mf_{rj} is calculated using equation (2), by (Rane and Uphade, 2015)

$$mf_{rj} = \frac{Q_c}{\frac{c_{rj}}{c_{cj}} cp_{cj}\left(t_{rj.evp.i} - t_{rj.evp.o}\right) + \left(1 - \frac{c_{rj}}{c_{cj}}\right)\left[h_{lat.ice} + cp_{ice}\left(t_{rj.evp.i} - t_{rj.evp.o}\right)\right]} \tag{2}$$

Average distribution coefficient is given by Chen *et al.*, 2014,

$$ADC = -0.1 + 0.32 \,.\, t_{fpd} - 0.04 \,.\, t_{fpd}^{\;2} + 0.12 \frac{V_{ice}}{V_{ss}^{\;0.5}} \tag{3}$$

ADC is the ratio of sugar in separated ice to sugar in bulk solution. Inclusion in ice is estimated using equation (3).

Heat duty of raw juice in LL_HE, $Q_{rj.llhe}$, is calculated using equation (4),

$$Q_{rj.llhe} = mf_{rj} \,.\, cp_{rj} \,.\, (t_{rj.llhe.i} - t_{rj.llhe.o}) \tag{4}$$

Power lost in cycling of thermal mass is calculated using equation (5)

$$Q_{th.lhe} = [(m_{lhe.ss.t} \,.\, cp_{ss} + m_{lhe.cu.t} \,.\, cp_{cu}) \,.\, (t_{rj.lhe.i} - t_{cj.lhe.o})]/time_{cal.dt} \tag{5}$$

It is deducted from cooling effect, Q_c, to obtain actual cooling available for freezing of water.

Overall heat transfer coefficient, U_o, is calculated using equation (6)

$$U_o = \frac{1}{\frac{1}{h_{rj} A_{ss.t.i}} + \frac{thk_{ss.t}}{k_{ss} A_{ss.t.i} \eta_{f.ss.t}} + \frac{thk_{ice}}{k_{ice} A_{ice.ss.t.i}} + \frac{thk_{tbm}}{k_{tbm} A_{cu.t.i}} + \frac{thk_{cu.t}}{k_{cu} A_{cu.t.i}} + \frac{1}{h_r A_{cu.t.i} \eta_{f.cu.t}}} \tag{6}$$

4. RESULTS AND DISCUSSIONS

Cooling coefficient of performance is 20 for R290 as refrigerant. It is 18 for R22 as refrigerant for same required operating conditions. Reduction in COP increases the condenser duty. It increases the CJ_HE load. Higher heat duty of CJ_HE on refrigerant side increases the exit temperature of concentrated juice temperature. Thus, stream of concentrated juice in LL_HE picks less heat from raw juice. It increases sensible cooling of raw juice in evaporator LHE. It utilizes the useful cooling effect in subcooling of raw juice rather than its utilization for freezing of water from juice. p-h and t-s diagram for FPCS are shown in Figure 5.

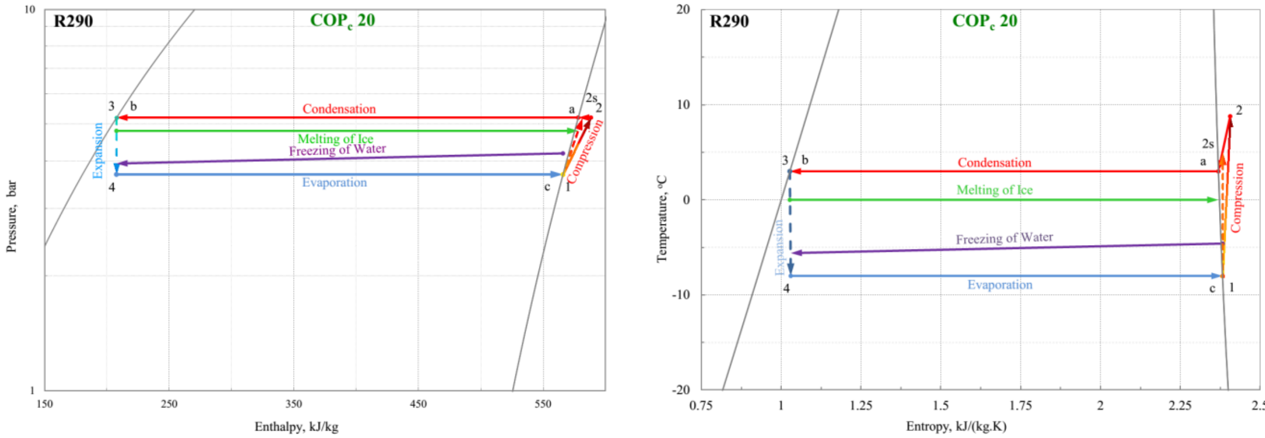
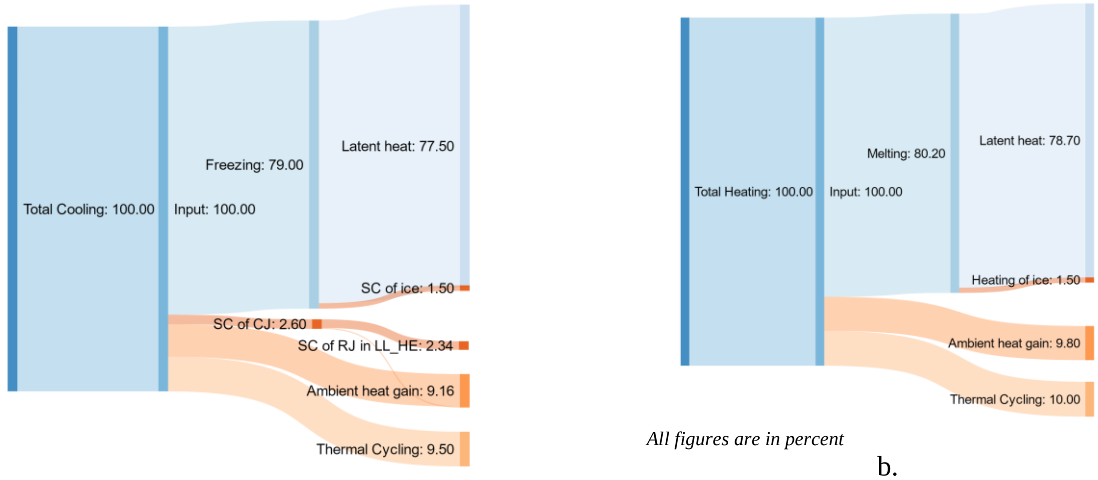


Figure 5: p-h and t-s Diagram for FPCS

Temperature of refrigerant at compressor outlet is 8.4ºC. It increases to 13ºC for R744 and 11ºC for R22. Enthalpy of refrigerant at compressor outlet depends on choice of refrigerant. It is low for refrigerant having lesser adiabatic index. It is 1.21 for R290, mentioned in Table 2. Hence, outlet temperature also increases as for refrigerants having higher adiabatic index. It is 1.9 for R744. Refrigerant temperature reaches to 13ºC as compare to 8.4ºC in case of R290. Superheat of CJ_HE is less for R290. It reduces size and cost of heat exchanger. Reduction in heat duty of CJ_HE allows the concentrated juice stream to receive more heat from raw juice stream in LL_HE and increases utilization of cooling effect for freezing of water. Performance of FPCS is simulated in Mathcad program. State point data for simple heat pump cycle is listed in

Table ***3*** for steady state condition. Water removal rate is 55.1 kg/h for 0.26 kW$_e$ electrical energy input. It gives specific energy consumption of 4.7 kWh/m^3 of water. Energy consumption is in the range of 9 to 12 kWh$_e$/m^3 of water separated, considering losses.



a. b.

Figure 6: Heat Balance in Latent Heat Exchanger: a. Evaporator and b. Condenser

Heat balance in LHE indicates that total useful cooling effect utilized in evaporator is 81.3% and total heating effect utilized in condenser is 80.2%. Ambient heat gain could be manage by selecting low thermal conductivity insulating material. Thermal cycling loss is worked out to 10% for 9.52 mm OD stainless steel tube. It decreases with increase in tube diameter but simultaneously overall heat transfer coefficient also reduces. Overall heat transfer coefficient for 7.52 mm ID tube reduces from 255 W/m^2.K at no ice layer to 90 W/m^2.K at 1.6 mm ice thickness.

Table 3: State Point Data for Simple Heat Pump Cycle for FPCS

LL_HE	**SP**	**#**	**Unit**	**CJ_HE**	**SP**	**#**	**Unit**
$mf_{rj.ll\_he.i}$	1	30.6	g/s	$mf_{cj.cj\_he.i}$	4	15.3	g/s
$Q_{rj.ll\_he}$	1-2	**3.22**	kW	$Q_{cj.cj\_he}$	5-6	**-0.16**	kW
$t_{rj.ll\_he.i}$	1	27.0	°C	$t_{cj.cj\_he.i}$	5	-4.6	°C
$t_{rj.ll\_he.o}$	2	-1.5	°C	$t_{cj.cj\_he.o}$	6	-2.5	°C
				$cp_{r.v.lhe.o}$	d	1.8	kJ/kg.K
$mf_{cj.lhe.o}$	4	15.3	g/s	$\mathbf{mf_{r.cmp.i}}$	a	**15.8**	**g/s**
$Q_{cj.ll\_he}$	7-8	**-1.52**	kW	$Q_{r.cj\_he}$	b-c	**0.16**	kW
$t_{cj.ll\_he.i}$	7	-2.5	°C	$t_{r.cj\_he.i}$	b	8.4	°C
$t_{cj.ll\_he.o}$	8	25.0	°C	$t_{r.cj\_he.o}$	c'	3.0	°C
$mf_{cw.lhe.o}$	4'	15.3	g/s	**Compressor**			
$Q_{cw.lhe}$	9-10	**-1.70**	kW				
$t_{cw.lhe.i}$	9	0.0	°C	COP_c		**20**	
$t_{cw.lhe.o}$	10	25.0	°C	$W_{cmp.e.i}$	a-b	**0.26**	kW
LHE1 (Evaporator)				**LHE2 (Condenser)**			
$mf_{rj.lhe.i}$	3	30.6	g/s				
$mf_{cw.lhe.o}$	4	15.3	g/s	$mf_{cw.lhe.o'}$	4'	15.3	g/s
$mf_{cj.lhe.o}$	4	15.3	g/s				
$Q_{cw.lhe}$	3-4	**5.13**	kW	$Q_{cw.lhe'}$	3'-4'	**-5.28**	kW
$Q_{cj.lhe}$	3-4	**0.15**	kW				
$t_{cw.lhe.i}$	3	-1.5	°C	$t_{cw.lhe.i'}$	3'	-4.6	°C
$t_{cw.lhe.o}$	4	-4.6	°C	$t_{cw.lhe.o'}$	4'	0.0	°C
$t_{cj.lhe.i}$	3	-1.5	°C				
$t_{cj.lhe.o}$	4	-4.6	°C				
$t_{r.lhe.evp}$	c	**-7.6**	°C	$t_{r.lhe.cnd}$	c'	**3.0**	°C
$p_{r.lhe.evp}$	c	3.9	bar	$p_{r.lhe'.cnd}$	c	5.5	bar
$x_{r.lhe.evp}$	c	6.8	%	R_p		1.4	
$h_{r.lhe.evp}$	c	181.2	kJ/kg	$h_{r.lhe.cnd}$	c'	578.2	kJ/kg
$h_{r.lhe.evp}$	d	566.4	kJ/kg	$h_{r.lhe.cnd}$	d'	207.5	kJ/kg
$h_{r.fg.lhe.evp}$	c-d	358.9	kJ/kg	$h_{r.fg.lhe.cnd}$	c'-d'	370.6	kJ/kg
$Q_{r.lhe.evp}$	c-d	**-5.28**	kW	$Q_{r.lhe.cnd}$	c'-d'	**5.38**	kW
$\rho_{r.l.lhe.evp}$	a	538.6	kg/m^3	$\rho_{r.l.lhe.cnd}$	d'	524.6	kg/m^3

Energy Balance on Refrigerant Side of FPCS

$Q_{in} = Q_{r.evp.lhe} + Q_{cmp.e} = \mathbf{-5.54\ kW}$

$Q_{out} = Q_{r.cnd.dsh.lhe} + Q_{r.cnd} = \mathbf{5.54\ kW}$

Energy Balance on Solution Side of FPCS

$Q_{in} = Q_{rj.llhe.12} + Q_{cj.lhe.34} + Q_{cw.lhe.34} = \mathbf{8.32\ kW}$

$Q_{out} = Q_{cw.lhe.3'4'} + Q_{cj.cjhe.56} + Q_{cj.llhe.78} + Q_{cw.llhe.910} = \mathbf{-8.32\ kW}$

5. CONCLUSIONS

Investigations on selective freezing of water from sugarcane juice using low lift heat pump are presented for jaggery making. R290 is suitable refrigerant for low lift reversible heat pump. It reduces the heat duty of LHE by maintaining low temperature at compressor out and helps to maintain almost equal heat duties of evaporator and condenser LHEs. Thermal cycling losses of LHEs are reduced to 11% by selecting SS304 tube with OD 9.52 mm. Cooling effect is utilized for freezing of water up to two-third of internal volume of tube. Low thermal conductivity of ice limits to select the higher diameter tube. Cooling COP is 20 for -8°C evaporator and 3°C condenser temperature. Overall system COP is 10 to 13, considering losses due to thermal cycling of LHEs, ambient heat gain, variation in freezing point depression and ice layer thickness. System Carnot efficiency is in the range of 41 to 54%. Power required for 1.5 TR FPCS is 0.4 to 0.6 kW_e. Achievable energy consumption is in the range of 9 to 12 kWh_e/m^3 of water separated.

NOMENCLATURE

c	concentration, °Brix
cp	specific heat at constant pressure, kJ/kg.K
d	diameter, m
h	enthalpy, kJ/kg
mf	mass flow rate, kg/s
p	pressure, bar
Q	heat duty, kW
t	temperature, °C
thk	thickness, m
v	velocity, m/s
x	quality, %
W	power, kW
ρ	density, kg/m^3
η	efficiency, %

Abbreviations

COP	Coefficient of Performance
FPCS	Freeze Pre-concentration System
SP	State Point

Subscripts

av	average
c	cooling
crnt	carnot
cj	concentrated juice
cmp	compressor
cnd	condenser/condensation
cw	cold water
e	electrical
evp	evaporator/evaporation
fpd	freezing point depression
i	inlet
ice	ice
ise	isentropic
lat	latent
o	outlet
r	refrigerant
rj	raw juice
ss	sugar solution
vol	volume/volumetric

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