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2016 Purdue Conferences
Compressor Engineering
Refrigeration and Air Conditioning
High Performance Buildings

HEAT PUMP FOR ENERGY EFFICIENT SUGARCANE JUICE FREEZE PRE-CONCENTRATION

Paper # 22423

11/07/2016 13:40 to 14:00

218 A&B, Stewart Center, Purdue University

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OUTLINE OF PRESENTATION

22423, 11/07/2016 13:40 to 14:00 Rm# 218 A&B

Heat Pump for Energy Efficient Sugarcane Juice Freeze Pre-Concentration

- ***Conventional Jaggery Making Process***
  - » Processes involved and their importance, mass balance
- ***Limitations of CJMP***
  - » Low furnace heat utilization efficiency, bagasse consumption, number of pans
  - » High pan surface temp during boiling, colour of jaggery, strenuous operation
- ***Freeze Concentration Process and System***
  - » Selective of water removal, low temp operation, maintains colour jaggery
- ***Selection of Refrigerant***
  - » R744, R717, **R290**, R22, R134a, R600, R410a, R407c
- ***Tube-Tube Heat Exchanger***
  - » Double wall vented tubes, reliable, high heat transfer coefficient, less dp
- ***Effect of LHE Thermal Mass***
  - » Ratio of ice to total enthalpy 89% for OD 9.52 mm x 1 mm thick SS tube
- ***FPCS Performance: 10 to 13 COP_c , 9 to 12 kWh_e/m^3 water***

CONVENTIONAL JAGGERY MAKING PROCESS

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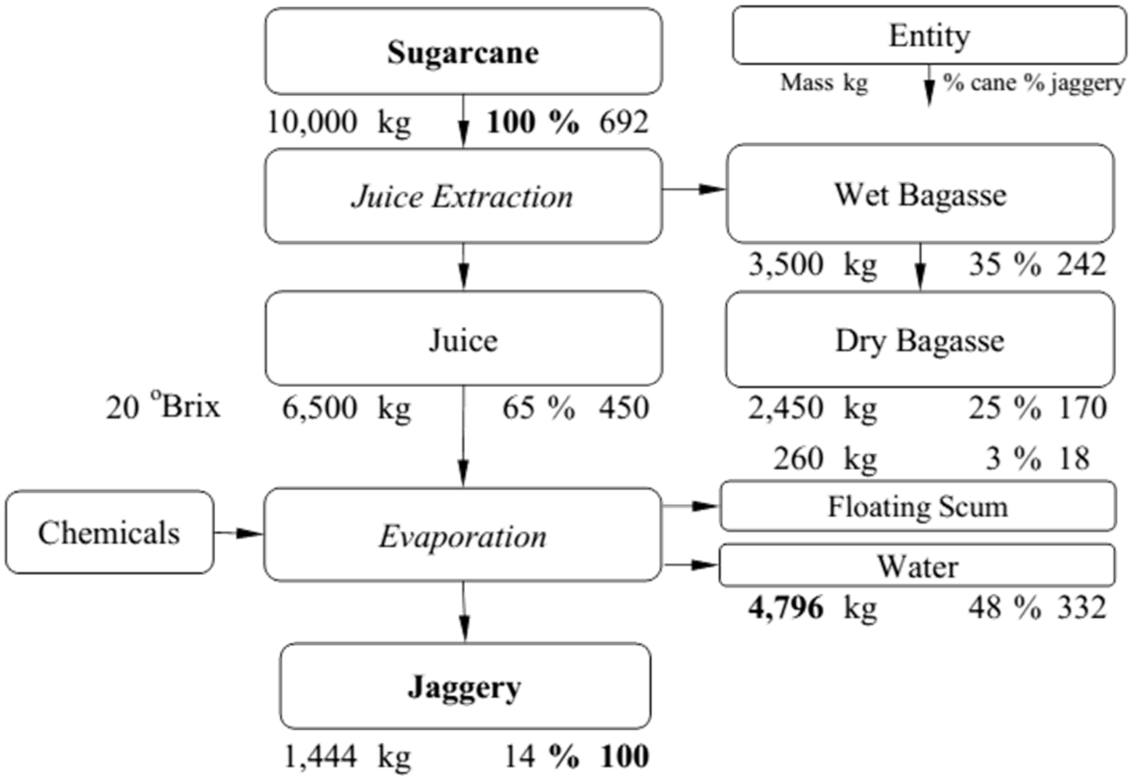
Rane and Uphade, 2015

Flow Diagram and Processes



- ***Juice Extraction***
  - » Crusher 1 to 2 stages compression
  - » ~ 60 to 70% juice extraction
- ***Evaporation in Open Pan***
  - » Juice heating 30°C to 85°C
  - » Lady's finger mucilage, lime, H_3PO_4 addition
  - » Clarification: removal of floating impurities
  - » Direct heating using open pan furnace to **118°C**, to make super saturate solution
- ***Cooling of Jaggery***
  - » To form crystalline jaggery
  - » Maintain temperature before packing

CONVENTIONAL JAGGERY MAKING PROCESS

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Limitations

- ***Low Furnace Heat Utilization Efficiency***
  - » Single pan 15%, two pans 30% and four pans 55%
- ***Number of Pans***
  - » Utilizes heat of flue gases for juice preheating and water evaporation
    - – Increases initial and operating cost
- ***High Pan Surface Temperature during Boiling in Open Pan***
  - » Flue gas 950 to 1050^{o}C, pan surface 500 to 600^{o}C
- ***Caramelization of Sugar***
  - » Inversion of sucrose to form reducing sugars: glucose and fructose
    - – Gives dark brown colour to jaggery, reduces market value and shelf life
- ***Low Market Value than Golden Yellow Colour Jaggery***
  - » Dark brown colour of jaggery
- ***Strenuous Operation due to Exposure to High Temperature Sources***
  - » Feeding of bagasse to furnace, stirring, scum removal operation in pan/s

PHASE EQUILIBRIUM DIAGRAM

Mathlouthi and Reiser, 1995

Sucrose - Water

- ***Phases***

  Solid
  - Sucrose
  - Ice

  Liquid
  - Solution
    - Sucrose
    - Water

- ***Eutectic Point***

  -13.9°C, 63°Brix

- ***Freezing Concentration***

  ab: cooling process

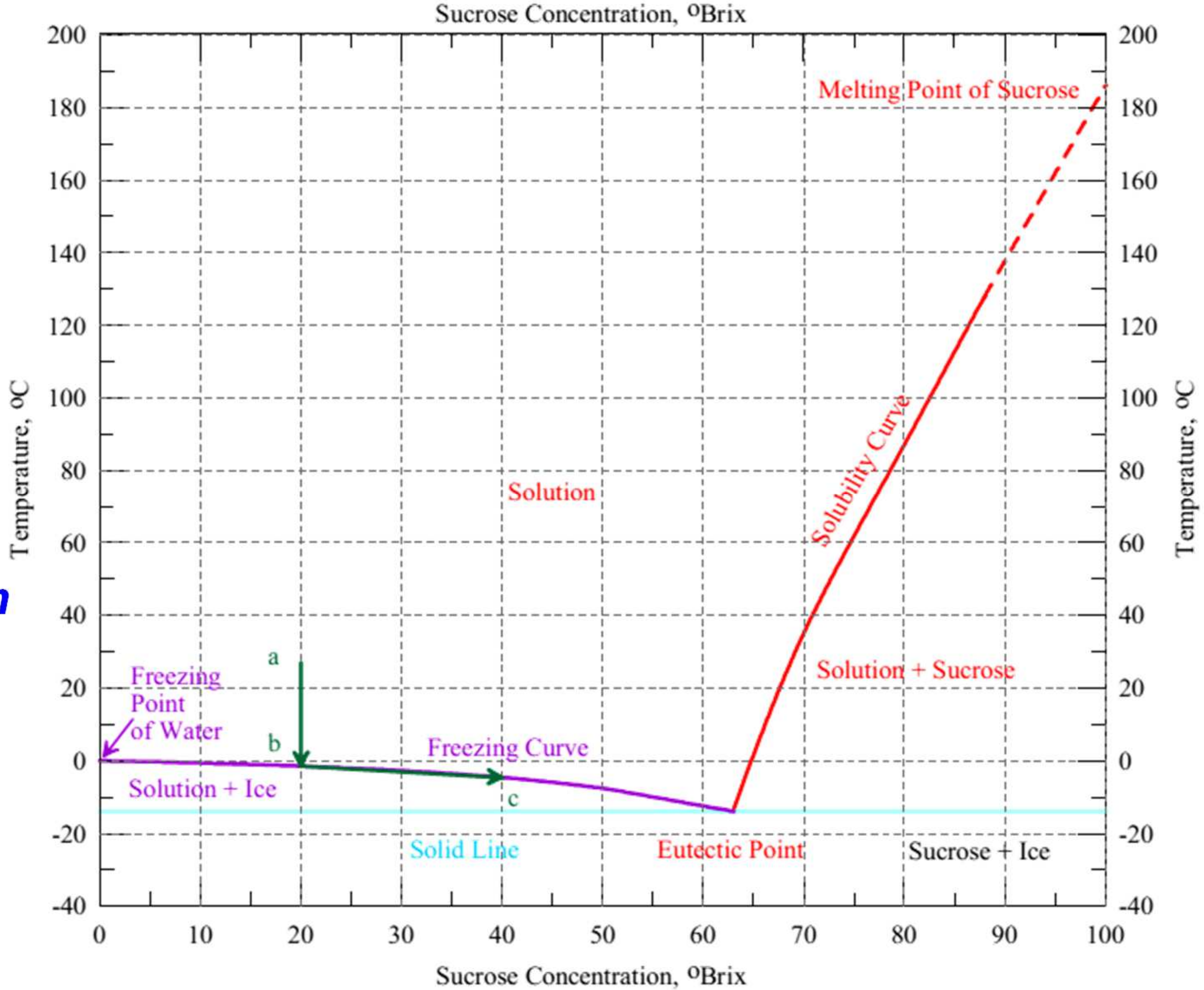
  bc: ice removal process

- ***Water Removal***

  $m_w = m_s \times (1 - c_{s.i}/c_{s.o})$

  $= 1\text{ kg} \times (1 - 20°Bx/40°Bx)$

  $= 0.5\text{ kg}$



FREEZE PRE-CONCENTRATION SYSTEM

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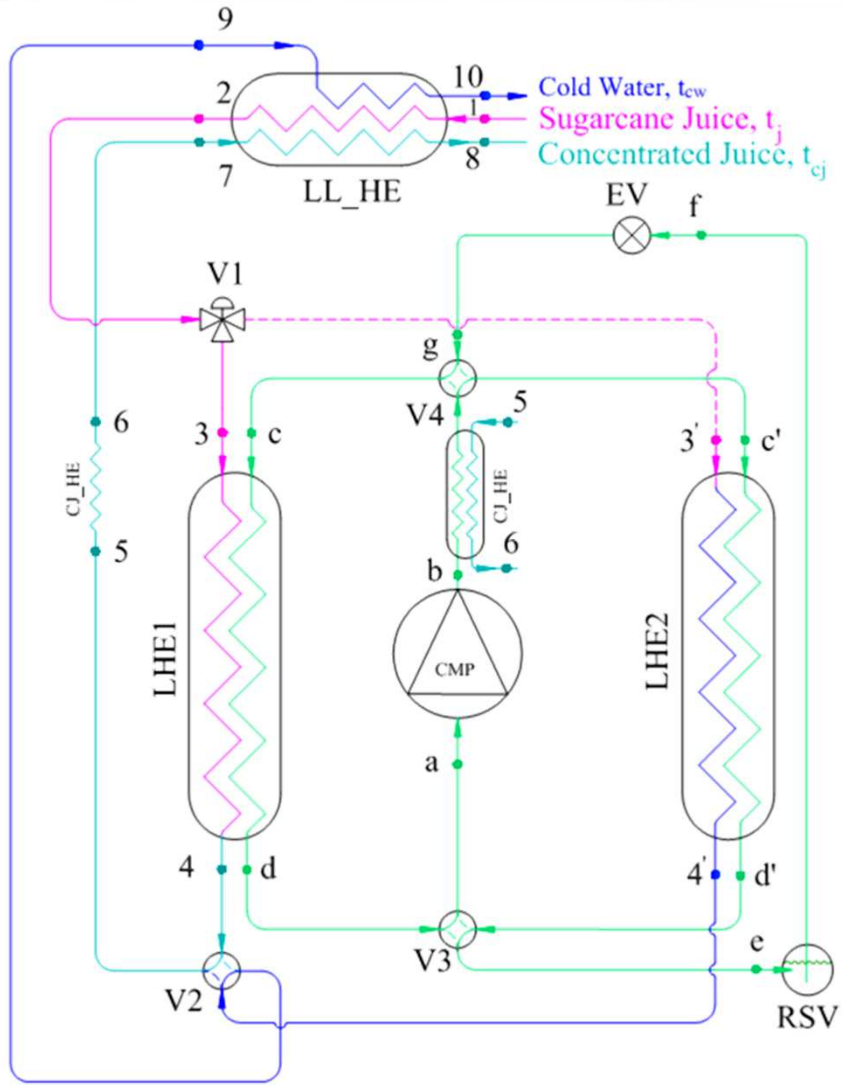
Heat Pump based Sugarcane Juice Pre-concentration 20 to 40°Brix



- ## *Nomenclature*

alphabets	refrigerant state
CMP	compressor
CJ_HE	concentrated juice heat exchanger
EV	expansion valve
LHE1 and 2	latent heat exchangers
LL_HE	liquid-liquid heat exchanger
RSV	reservoir
V1	three way valve
V2,V3 andV4	four way valve
#	fluid state

- ## *First Half Cycle*

Refrigerant	a-b-c-d-e-f-g-c'-d'-a
Sugar solution	1-2-3-4-5-6-7-8
Water	4'-9-10

- ## *Second Half Cycle*

Refrigerant	a-b-c'-d'-e-f-g-c-d-a
Sugar solution	1-2-3'-4'-5-6-7-8
Water flow	4-9-10

FREEZE PRE-CONCENTRATION SYSTEM

LHE 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*

- ***Continuous Operation***
  - » LHE operation switches from/to evaporator ↔ condenser
- ***Condenser Heat Duty = Evaporator Load + Compressor Work***
- ***Identical LHEs with CJ_HE***
  - » If $Q_{lhe.cnd}\uparrow$, $t_{cw.lhe.cnd.o}\uparrow$, $p_{r.cnd}\uparrow$, $R_{pr}\uparrow$, $W_{cmp.e.i}\uparrow$, $COP_c\downarrow$
    - – Requires CJ_HE to ↑ system COP_c by ↓ $t_{cw.lhe.o}$

FREEZE PRE-CONCENTRATION SYSTEM

R290 Preferred Refrigerant for FPCS

	Refrigerant	**ODP**	**GWP_{100}**	**p** *at -8°C* **bar**	**p** *at 3°C* **bar**	**t** *critical* **bar**	**t** *critical* **°C**	**h_{lat}** at -8°C **kJ/kg**	**$\rho_{v.cmp.i}$** at -8°C **kg/m^3**	**γ_v** at -8°C	**Major Issues**
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

- ***R290: Natural refrigerant, low GWP, low charge, low superheat temperature***
  - » m_r 360 g / 1.5 TR, 0.004 kg/m^3, class A3, LFL 0.1 kg/m^3, $t_{r.cmp.o}$ 9°C

EFFECT OF THERMAL MASS

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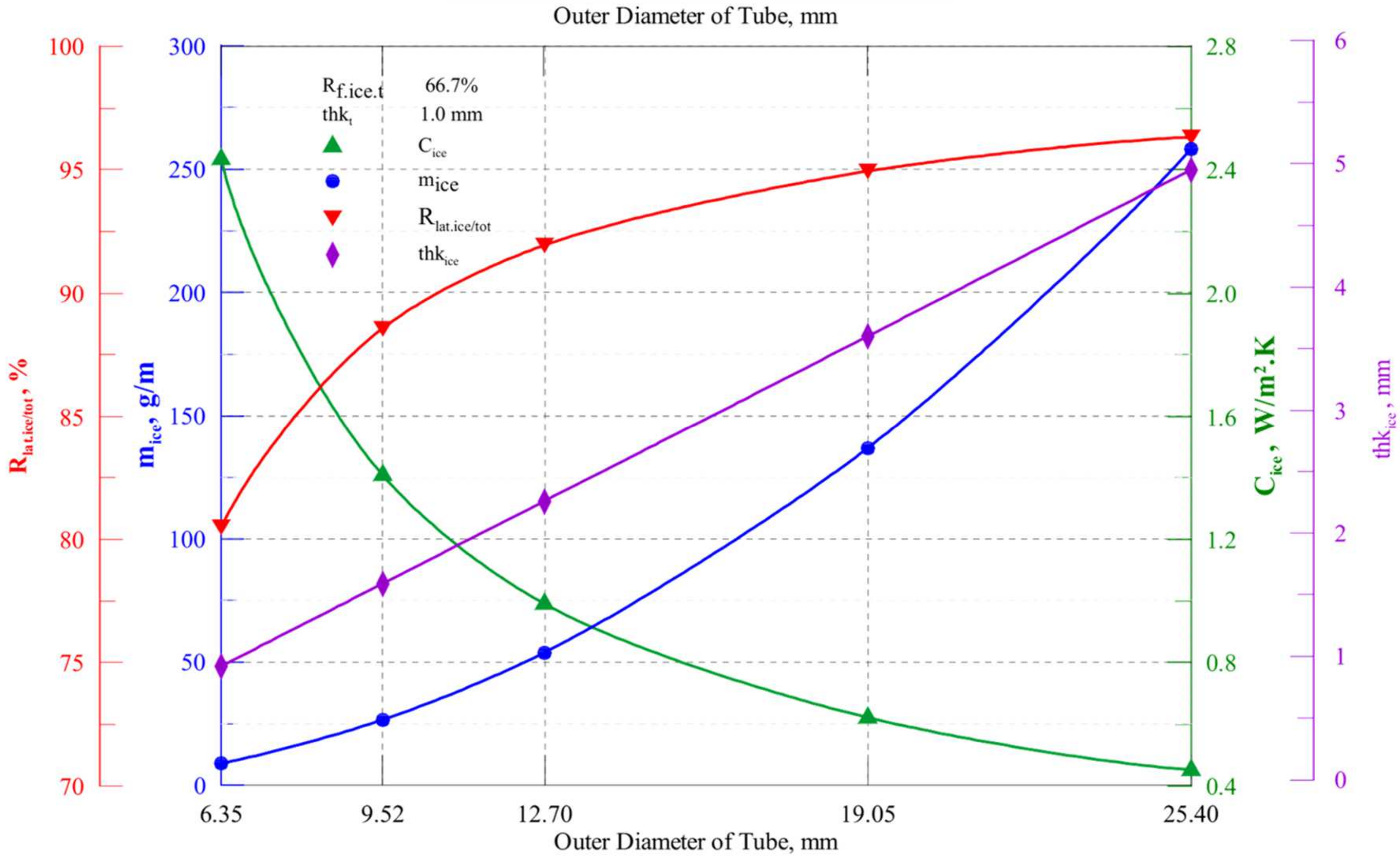
OD 9.52 mm x 1 mm thk, $R_{lat.ice/tot}$ 89%, TT_HE, SS-Cu Tube

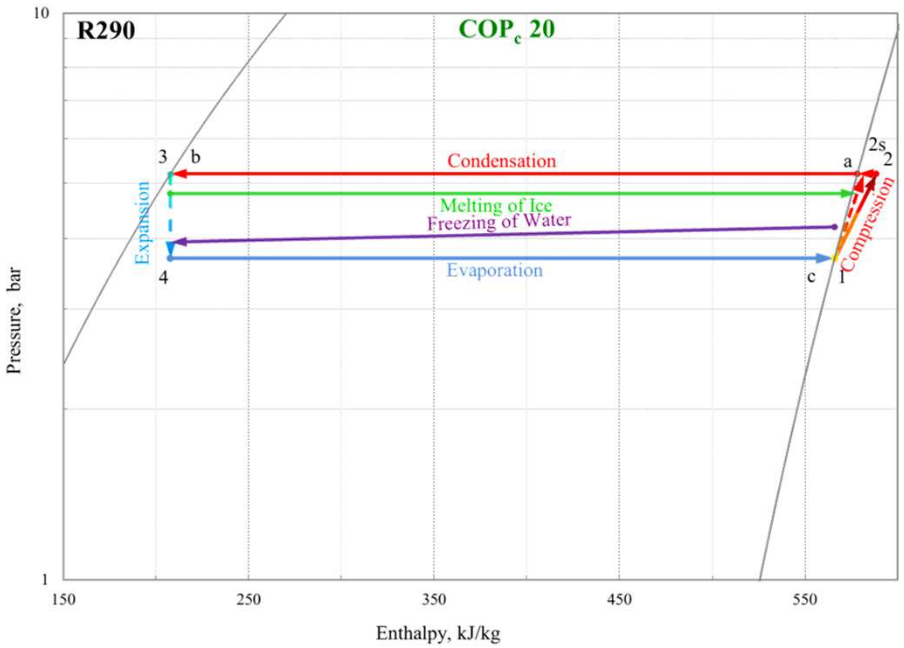


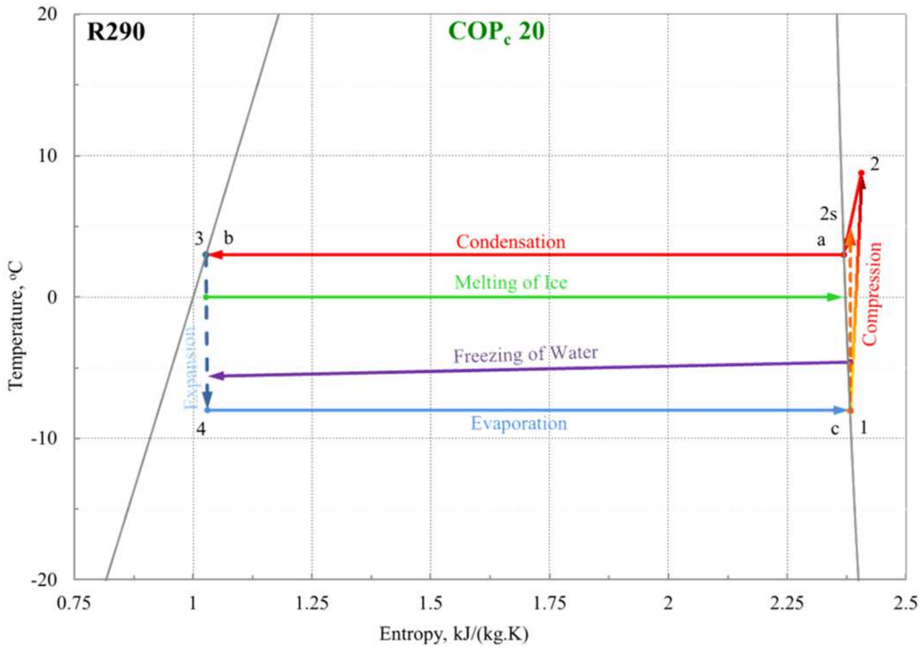
- ***OD 9.52, 1 Thk >> $time_{hlf.cyc}$ 180 s, $n_{cyc/h}$, 20 cyc/h***
  - » $R_{f.ice.t}$ 66.7%, thk_{ice} 1.6 mm, $m_{ice.hlf.cyc}$ 29 g/m, C_{ice} **1.4 kW/m².K**, $R_{lat.ice/tot}$ **89%**

PERFORMANCE OF HEAT PUMP

R290

p-h and t-s Diagram





- ***$h_{r.cmp.o}\uparrow$, $Q_{cj.cj\_he}\uparrow$, $Q_{cj.ll\_he}\downarrow$, $t_{rj.ll\_he.o}\uparrow$, $Q_{c.cmp>lat.ice}\downarrow$***
  - » $t_{r.cmp.o}$ 13°C R744, **9°C R290**, 11°C R22
- ***$COP_c\uparrow$, $Q_{cnd}\downarrow$, $Q_{lhe.cnd}\downarrow = Q_{lhe.evp}$ (f) + $Q_{cj.cj\_he}\downarrow$***

STATE POINT DATA & PERFORMANCE OF FPCS

MathCAD Simulation

R290, Q_c 1.5 TR, W_c 0.26 kW, COP_c 20

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LL_HE	SP	#	Unit
$mf_{rj.ll\_he.i}$	1	30.6	g/s
$Q_{rj.ll\_he}$	1-2	**3.22**	kW
$t_{rj.ll\_he.i}$	1	27.0	ºC
$t_{rj.ll\_he.o}$	2	-1.5	ºC
$mf_{cj.lhe.o}$	4	15.3	g/s
$Q_{cj.ll\_he}$	7-8	**-1.52**	kW
$t_{cj.ll\_he.i}$	7	-2.5	ºC
$t_{cj.ll\_he.o}$	8	25.0	ºC
$mf_{cw.lhe.o}$	4'	15.3	g/s
$Q_{cw.lhe}$	9-10	**-1.70**	kW
$t_{cw.lhe.i}$	9	0.0	ºC
$t_{cw.lhe.o}$	10	25.0	ºC

CJ_HE	SP	#	Unit
$mf_{cj.cj\_he.i}$	4	15.3	g/s
$Q_{cj.cj\_he}$	5-6	**-0.16**	kW
$t_{cj.cj\_he.i}$	5	-4.6	ºC
$t_{cj.cj\_he.o}$	6	-2.5	ºC
$cp_{r.v.lhe.o}$	d	1.8	kJ/kg.K
$mf_{r.cmp.i}$	a	**15.8**	**g/s**
$Q_{r.cj\_he}$	b-c	**0.16**	kW
$t_{r.cj\_he.i}$	b	8.4	ºC
$t_{r.cj\_he.o}$	c'	3.0	ºC

Compressor			
$W_{cmp.e.i}$	a-b	**0.26**	kW
COP_c		**20**	

- ***Used to Estimate the Energy Balance on Refrigerant and Solution Flows***

STATE POINT DATA & PERFORMANCE OF FPCS

MathCAD Simulation, R290

LHE1 and LHE2

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LHE1 (Evaporator)

$mf_{rj.lhe.i}$	3	30.6	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
$Q_{cj.lhe}$	3-4	**0.15**	kW
$t_{cw.lhe.i}$	3	-1.5	°C
$t_{cw.lhe.o}$	4	-4.6	°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
$p_{r.lhe.evp}$	c	3.9	bar
$x_{r.lhe.evp}$	c	6.8	%
$h_{r.lhe.evp}$	c	181.2	kJ/kg
$h_{r.lhe.evp}$	d	566.4	kJ/kg
$h_{r.fg.lhe.evp}$	c-d	358.9	kJ/kg
$Q_{r.lhe.evp}$	c-d	**-5.28**	kW
$\rho_{r.l.lhe.evp}$	a	538.6	kg/m^3

LHE2 (Condenser)

$mf_{cw.lhe.o'}$	4'	15.3	g/s
$Q_{cw.lhe'}$	3'-4'	**-5.28**	kW
$t_{cw.lhe.i'}$	3'	-4.6	°C
$t_{cw.lhe.o'}$	4'	0.0	°C
$t_{r.lhe.cnd}$	c'	**3.0**	°C
$p_{r.lhe'.cnd}$	c	5.5	bar
R_p		1.4	
$h_{r.lhe.cnd}$	c'	578.2	kJ/kg
$h_{r.lhe.cnd}$	d'	207.5	kJ/kg
$h_{r.fg.lhe.cnd}$	c'-d'	370.6	kJ/kg
$Q_{r.lhe.cnd}$	c'-d'	**5.38**	kW
$\rho_{r.l.lhe.cnd}$	d'	524.6	kg/m^3

ENERGY BALANCE

MathCAD Simulation, R290

Refrigerant and Solution

- ***Refrigerant Side***

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

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

- ***Solution Side***

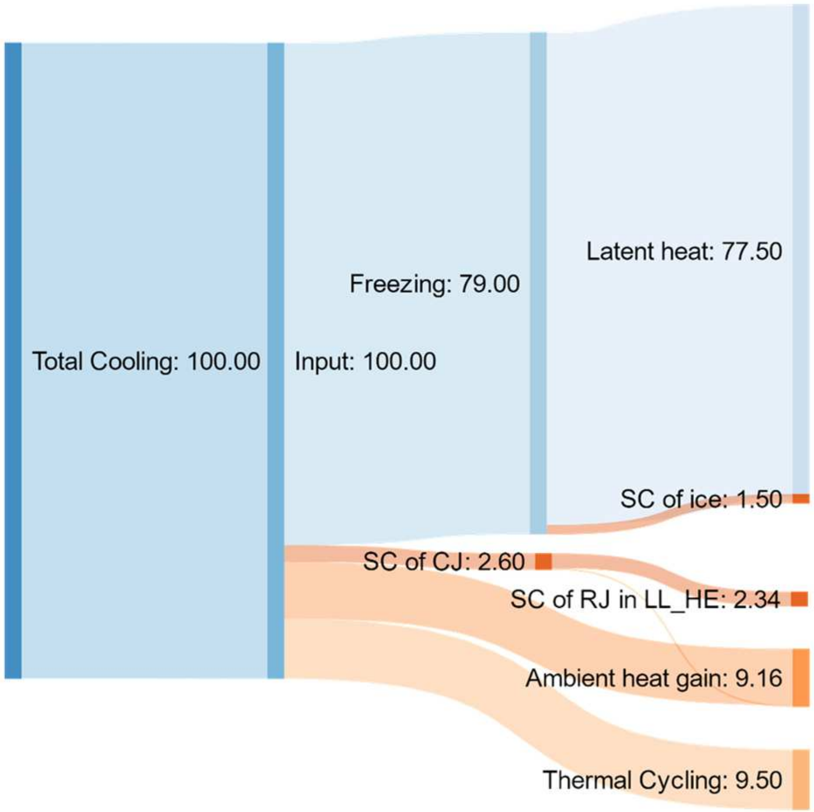
  $Q_{in} = Q_{rj.llhe.12} + Q_{cj.lhe.34} + Q_{cw.lhe.34} = \mathbf{8.32\ kW}$

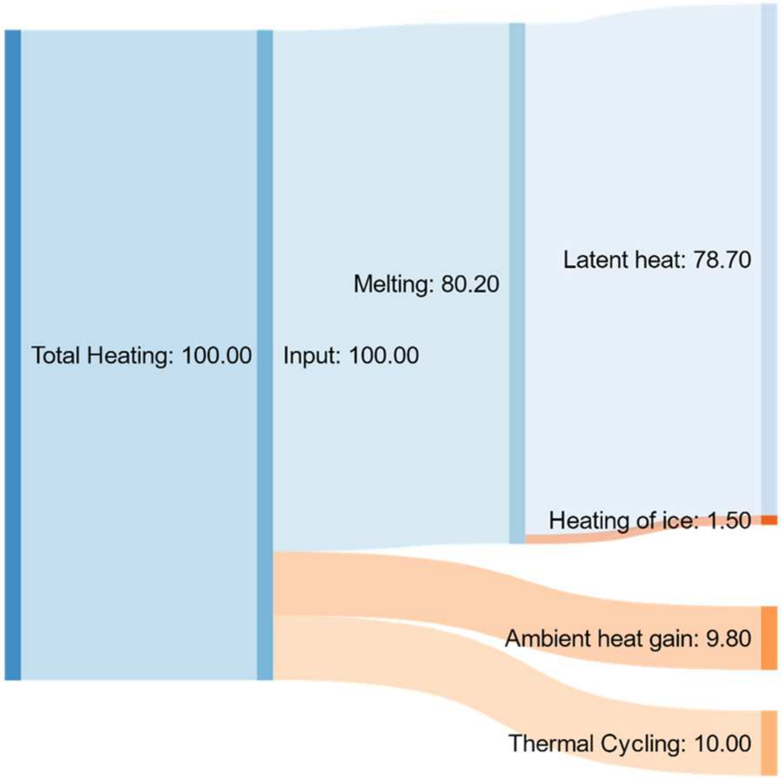
  $Q_{out} = Q_{cw.lhe.3'4'} + Q_{cj.cjhe.56} + Q_{cj.llhe.78} + Q_{cw.llhe.910} = \mathbf{-8.32\ kW}$

- ***Solution Side Heat Duty > Refrigerant Side Heat Duty***
  - » Internal heat circulation
    - – LL_HE--pre-cooling of raw juice
      - Using flow streams of cold water and concentrated juice
    - – CJ_HE--recover condenser superheat
      - Using concentrated juice
        - » Reduces $t_{cw.lhe.cnd.o}$

LATENT HEAT EXCHANGER

Heat Balance





- ***$Q_{c.lat.ice}$ 81.3% (77.5% + 1.5% + 2.34%) $Q_{h.lat.ice}$ 80.2% (78.7% + 1.5%)***
  - Due to cooling of CJ, $Q_{c.lat.ice} > Q_{h.lat.ice}$
- ***$Q_{th.cyc.lhe}$ ~10% Q_{lhe} and Q_{amb} ~9.5% Q_{lhe}***

CONCLUSIONS

Heat Pump for Energy Efficient Sugarcane Juice Freeze Pre-Concentration

- ***Conventional Jaggery Making Process***
  - » Low furnace heat utilization efficiency, high boiling temperature, dark brown colour jaggery, low market value, strenuous operation
- ***Investigated Selective Freezing of Water from Sugarcane Juice***
  - » Energy efficient low lift reversible heat pump
  - » Continuous operation using switching of LHEs
- ***R290 Selected as Environmental Friendly Refrigerant***
  - » Natural refrigerant, no ODP, low charge, low superheat temperature
- ***Thermal Cycling Loss in LHE Reduced to 11%***
  - » Using OD 9.52 mm x 1 mm thick SS tube
  - » Ice fill ratio of tube 2/3rd of internal volume
  - » Low k_{ice} and heat transfer coefficient limits diameter tube
- ***FPCS with R290: 10 to 13 COP_c , 9 to 12 kWh_e/m^3 water Achievable***
  - » COP_c 20 at t_{evp} -8°C and t_{cnd} 3°C, 0.26 kW_e , 4.7 kWh_e/m^3

THANKS