IOP Conf. Series: Materials Science and Engineering **232** (2017) 012004 doi:10.1088/1757-899X/232/1/012004

Novel Long Stroke Reciprocating Compressor for Energy Efficient Jaggery Making

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Abstract: Novel Long Stroke Reciprocating Compressor is analysed for jaggery making while avoiding burning of bagasse for concentrating juice. Heat of evaporated water vapour along with small compressor work is recycled to enable boiling of juice. Condensate formed during heating of juice is pure water, as oil-less compressor is used. Superheat of compressor is suppressed by flow of superheated vapours through condensate. It limits heating surface temperature and avoids caramelization of sugar. Thereby improves quality of jaggery and eliminates need to use chemicals for colour improvement. Stroke to bore ratio is 0.6 to 1.2 in conventional reciprocating drives. Long stroke in reciprocating compressors enhances heat dissipation to surrounding by providing large surface area and increases isentropic efficiency by reducing compressor outlet temperature. Longer stroke increases inlet and exit valve operation timings, which reduces inertial effects substantially. Thereby allowing use of sturdier valves. This enables handling liquid along with vapour in compressors. Thereby supressing the superheat and reducing compressor power input. Longer stroke increases stroke to clearance ratios which increases volumetric efficiency and ability of compressor to compress through higher pressure ratios efficiently. Stress-strain simulation is performed in SolidWorks for gear drive. Long Stroke Reciprocating Compressor is developed at Heat Pump Laboratory, stroke/bore 292 mm/32 mm. It is operated and tested successfully at different speeds for operational stability of components. Theoretical volumetric efficiency is 93.9% at pressure ratio 2.0. Specific energy consumption is 108.3 kWh_e/m^3 separated water, considering free run power.

1. Introduction

Jaggery is the traditional sweetener in India. It is preferred for consumption due to its medicinal values. It is conventionally prepared by evaporation of water for concentration of sugarcane juice in open pan boiling. Bagasse, which is residue of juice extraction, is used as fuel. Pan surface temperature is high due to hot flue gases, which has temperature about 950 to 1050°C at chimney end (Sardeshpande *et al.*, 2010). Hot spots are formed due to high temperature pool boiling of sugarcane juice in mild steel or stainless steel pan. It causes caramelization of sugar and gives dark brown colour to jaggery. Dark brown jaggery has less market value than golden yellow jaggery (Guddadamath *et al.*, 2014). Chemical clarificants like lime, sodium hydroxide, phosphoric acid are used to clarify juice and improve colour of jaggery (Shiralkar *et al.,* 2014). Traces of these chemicals are harmful to human health. Hence, chemical free or organic jaggery should be produced. Chemical free or organic jaggery can be produced if pan surface temperature maintained to or below 100°C and clarify juice using vegetative clarificants only. These issues are addressed by energy efficient vapour recompression for jaggery making using Long Stroke Reciprocating Compressor.

This paper mainly reports development of small capacity Long Stroke Reciprocating Steam Compressor and its use in Vapour Recompression System for jaggery making. This paper also reports the performance of Vapour Recompression System for jaggery making, which addresses the issues of conventional jaggery making.

1.1. Vapour recompression based jaggery making

Vapour Recompression System, VRCS, consists of Latent Heat Exchanger, LHE, and compressor. LHE comprises horizontal flat oval tube, which is kept inside a horizontal circular tube, alternatively a rectangular tube to accommodate more number of flat oval tubes. Inside space of flat oval tube serves as evaporator. It is filled with raw juice, generally it occupies 50% of internal volume of tube, as shown in figure 1. Space between flat oval tube and circular tube is condenser. Compressed vapours introduced in condenser where they are condensed by delivering its latent heat of condensation to evaporate water from juice in the evaporator.

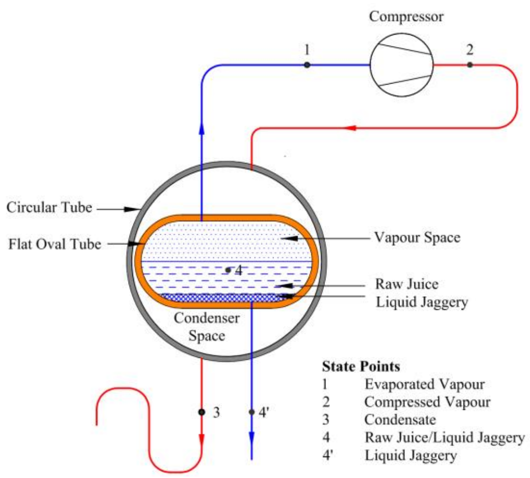

Figure 1: VRCS for Sugarcane Juice Concentration

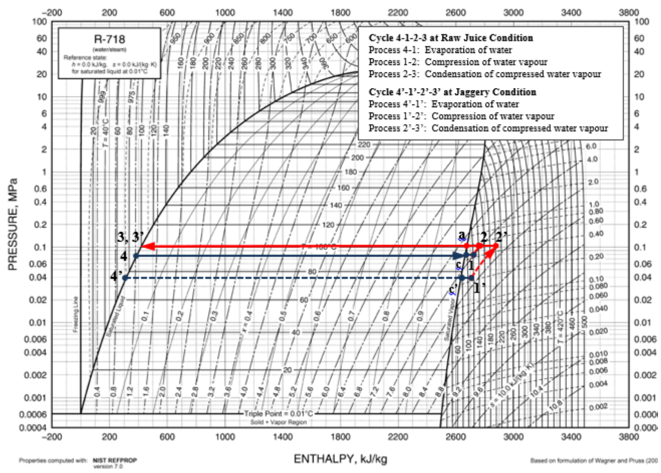

Figure 2: Heat Pump Cycle on p-h diagram R718

1.1.1. Working

Initially, saturated air is evacuated from evaporator and then compressed using Long Stroke Reciprocating Compressor. Due to low pressure in evaporator, moisture carrying capacity of air increases, thus, more moisture is removed. It increases temperature and pressure of compressed air. At high pressure, moisture carrying capacity of air reduces. Simultaneously, heat transfer from condenser to evaporator increases temperature of juice and reduces condenser temperature. This helps to condense out moisture, and increase the evaporator temperature, increases moisture carrying capacity of air in evaporator. Air evacuation from evaporator occurs for very short duration. After this, compressor compresses wet or saturated water vapour and it is condensed in the condenser in later phase. Condensate continuously drained through steam trap valve. Working cycle is represented on the R718 p-h chart, figure 2. Remaining solution gets enrich in jaggery constituents. Discharge pressure is atmospheric pressure, process 2-a-3 or 2'-a-3'. Evaporator pressure reduces from atmospheric pressure, process 4-c-1 for raw juice to certain lower pressure, process 4'-c'-1'. It depends on boiling point elevation, heat exchange approach.

1.2. Necessity of Long Stroke Reciprocating Compressor

Concentration of juice increases as the water gets evaporated from raw juice. It increases the boiling point elevation of juice, from 0.5 to 18°C for 20 to 90°Brix change. Water removal rate is higher during initial phase of water removal due to low boiling point elevation and high heat transfer coefficient, 1.58 kW/(m^2.K). The worst case is at jaggery condition. Here, temperature lift is enlarged due to cumulative effect of 18°C boiling point elevation and higher temperature approach required for heat exchange, due to very low heat transfer coefficient, 0.06 kW/(m^2.K). Suction pressure reduces much below that of raw juice condition. Hence, compressor power required during final stage of jaggery making is higher than raw juice condition. Small capacity steam compressors are not available in market. Judicious design of

small capacity steam compressor saves power. Pressure ratio across the compressor is 1.05 to 2.8. Compressor with long stroke improves isentropic and volumetric efficiencies. Isentropic efficiency is the ratio of ideal work required during isentropic compression to the actual work required. Isentropic efficiency of compressor depends upon pressure ratio, working fluid, number of compression stages and use of intercooler in case of multistage compressor. Isentropic efficiency can be improved by heat transfer from cylinder wall during compression process. It is possible to construct compressor with isentropic efficiency greater than 100% (Hanlon, 2001). Heat transfer from cylinder wall can be improved either by providing fins or providing long stroke with or without fins on cylinder wall. Crank and connecting rod mechanism limits stroke to bore ratio in conventional reciprocating compressors. Similarly, volumetric efficiency of reciprocating compressor is limited due to inertial forces.
In this paper, development of long stroke reciprocating compressor is presented with bore 32 mm and stroke 292 mm. Stroke to bore ratio is 9.125. It increases surface area of cylinder by 9.1 times, similarly heat transfer rate also increases by 9.1 times compare to conventional compressors. Valve operation time gets increased due to longer stroke. It enables to use of sturdier valves and improves volumetric efficiency.

1.2.1. Stroke to bore ratio of reciprocating drives
Stroke to bore ratios in some engines are listed in table 1. Stroke to bore ratio is 0.6 to 1.2 in conventional

Table 1: Stroke to Bore Ratio and Piston Speed of Some Engines (Greenman, 1996)

Make/Model	Bore mm	Stroke/Bore Ratio	Mean Piston Speed m/s	Power kW	Application
Tee-Dee 0.1	6.0	0.95	6.10	0.08	R/C aircraft
Arden	12.6	1.04	4.98	0.40	R/C aircraft
Dooling 61	25.8	0.74	9.19	4.47	R/C aircraft
Olsson & Rice	31.8	0.87	11.68	2.57	Handtool
Fichtel & Sachs	38.1	**1.15**	15.14	23.72	Motorcycle
Evinrude	39.6	0.88	4.67	4.44	Outboard motor
Power Products	53.1	**0.60**	7.41	5.22	Home use
Chrysler 610	55.6	0.78	10.97	23.91	Outboard motor
MZ ES 150	61.0	0.98	14.99	**53.77**	Motorcycle
Chrysler 610	64.3	0.64	12.50	30.03	Outboard motor

1 bhp = 0.746 kW , R/C: Radio Controlled

reciprocating drives. It is also applicable for double acting opposed piston reciprocating compressors, as shown in figure 3.

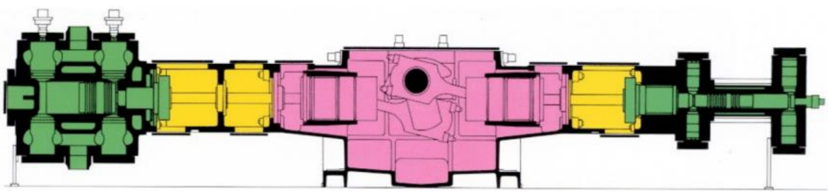

Figure 3: Conventional Opposed Piston Reciprocating Compressor (Bloach, 2006)

Reciprocating compressors can be operated more efficiently by increasing the stroke to bore ratio. In conventional machines, stroke to bore is limited as connecting rod strikes the cylinder wall at high stroke to bore ratio, while stroke accommodation is the issue at lower stroke to bore ratios. Long stroke in reciprocating compressors allows high outer surface area of cylinder. It enhances the heat dissipation to surrounding and increases isentropic efficiency by reducing compressor outlet temperature. Superheat of compressed water vapour is suppressed by condensate formed inside the cylinder. Longer strokes increases the inlet and exit valve operation timings, which reduces inertial effects substantially. Thereby allowing use of sturdier valves. This enables handling liquid along with vapour in the compressors. Thereby supressing the superheat and reducing the compressor power input. Longer stroke increases the stroke to clearance ratios which increases the volumetric efficiency and ability of compressor to compress through higher pressure ratios efficiently.

2. Research Methodology

Initially, long stroke reciprocating drive is developed and then, it is tested for operational stability of components. Stress and strain analysis of pinion and rack assembly is performed in SolidWORKS. Theoretical performance of vapour recompression system using LSRC is simulated in MathCAD for eight equal stages of water removal for jaggery making. This paper presents the development of long stroke reciprocating steam compressor and its use for jaggery making. Development of compressor has been started with design and development of long stroke reciprocating drive for suitably selected long stroke cylinders which will assembled with the cylinders.

3. Novel Long Stroke Reciprocating Compressor

Long Stroke Reciprocating Compressor involves double acting opposed piston-cylinders, Long Stroke Gear Drive, LSGD, base frame, motor frame, flexible shaft, BLDC motor, check valves and connecting tubes. LSGD consists of rack assembly and pinion. Rack assembly is designed for known stroke of reciprocating piston-cylinder. Maximum force applied on tooth is estimated using known speed, power of motor and pitch circle diameter of pinion, which is initially taken close to piston diameter. Stresses are more critical at fillet of shaft and pinion and/or at the tooth base of pinion, rack or semi-circular internal gear. Stresses and deflection in pinion and rack assembly are simulated in SolidWorks.

3.1. Reciprocating cylinders

Reciprocating piston-cylinders suitable for compression of steam were selected. These are oil-free compression cylinders. Isometric view is shown in figure 4 and cut section is shown in figure 5.

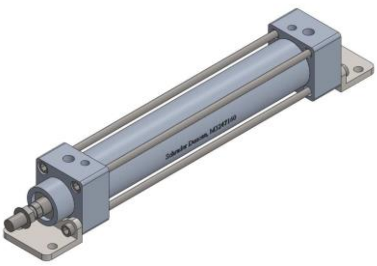

Figure 4: Cylinder

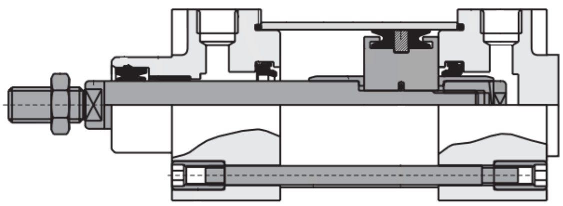

Figure 5: Cut Section of Cylinder

Available strokes of cylinder are 40, 50, 80, 100, 160, 250 and 300 mm. These cylinders can handle vapour in the range of -10 to 180ºC. High temperature viton seals are used. Stroke of selected cylinder is 300 mm and bore is 32 mm. Stroke of rack assembly is 292 mm for mild steel gear drive. It is limited to 292 mm, to avoid locking of rack assembly and pinion due to interference of strokes of gear drive and cylinders. If number of tooth on rack assembly increased by one, stroke of gear drive becomes higher than stroke of cylinder. It increases interference and movement of pinion gets restricted. Hence, gear drive stroke must be slightly lesser than cylinders.

3.2. Long stroke reciprocating drive

Patented Long Stroke Reciprocating Drive involves rack assembly, pinion, two pinion guides and three bearings (Rane and Metange, 2014, Rane and Uphade, 2016). Rack assembly is combination of two racks and two semi-circular internal gears, figure 6. One pinion guide, PG, is integral part of gear drive. It guides the pinion by rollover on racks and internal gears. Second pinion guide is integral part in the motor frame. It guides the pinion in transverse direction, along the offset length. Bottom bearing supports the bottom end of pinion and its outer race rolls on outer guide of pinion guide in rack assembly. Middle bearing supports the pinion at middle and its outer race rolls on internal top guide of pinion guide in rack assembly. Top bearing supports the flexible shaft end at top end of pinion shaft and its outer race rolls on pinion guide in motor frame.
When pinion rotates about shaft, it moves the rack and its movement is transferred to the connecting

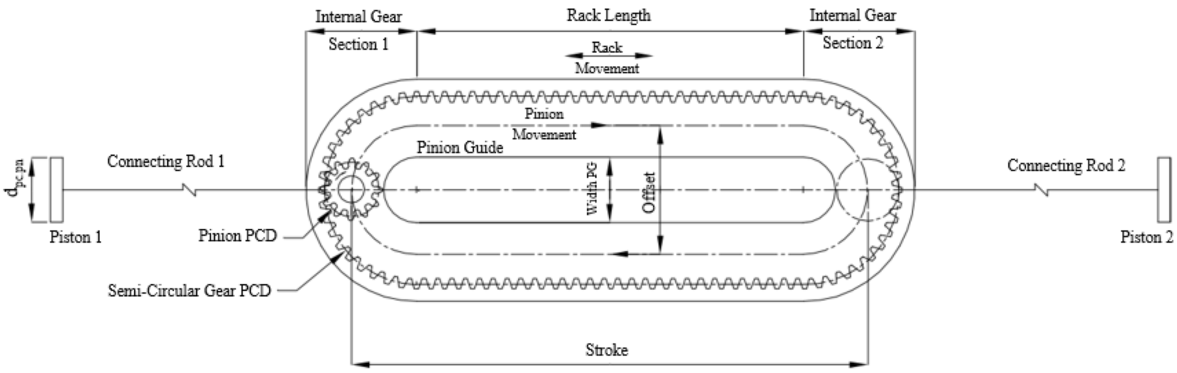

Figure 6: Long Stroke Reciprocating Drive

rods, which in turns moves the pistons. At the end of first rack, pinion smoothly rolls over the semi-circular internal gear from one rack to another rack and moves the piston by driving the second rack. Same cycle repeats for next rollover of pinion from rack to internal gear and vice-versa. Pinion is rotated about shaft using BLDC motor and pinion also oscillates along linear offset during rollover on semi-circular internal gears, while the rack assembly only reciprocates. In this way, rotary motion of motor is converted into long stroke reciprocating motion. Flexible shaft is an important component. It is rotated by motor at motor end. It rotates and oscillates at pinion end. Vapour recompression based jaggery maker is shown in figure 7. Details of developed LSRC compressor are listed in table 2.

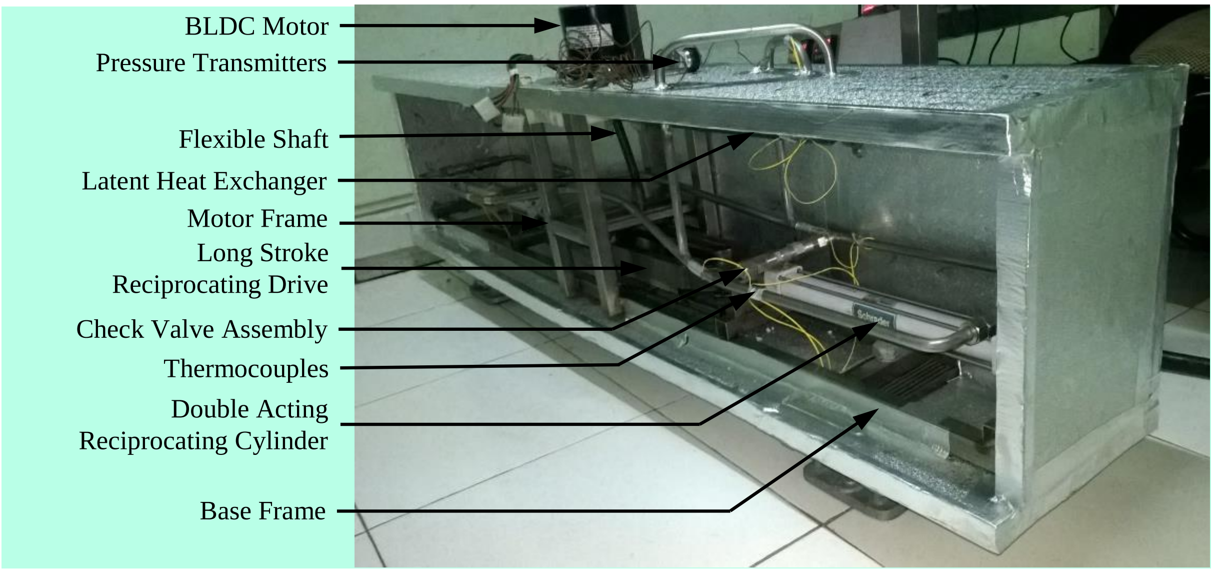

Figure 7: Vapour Recompression based Jaggery Maker

Table 2: Details of Long Stroke Reciprocating Compressor

Parameters	Abbreviation	Value	Unit
Speed of pinion	N_{pn}	720	rpm
Velocity of pinion and gear drive, $v_{pc.pn} = \pi\, d_{pn}\, N_{pn} / 60$	$v_{pc.pn}$	1.13	m/s
Bore	d_p	32	mm
Stroke of cylinder	l_{stk}	292	mm
Swept volume	vol_{stk}	234.8	cc
Clearance volume	vol_{cle}	7.36	cc
Volume of flow rate	$volf_{stk.ideal}$	1.409	L/s
Thrust required for pull and push single piston	$F_{pull/push}$	78.7	N
Vacuum developed	p_{suc}	720	mm_Hg vac

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4. Heat Transfer Coefficients

Water is evaporated from sugarcane juice in stainless steel flat oval tube. Heating source is extracted vapours from juice, compressed to atmospheric pressure. Overall heat transfer is 1.58 kW/(m^2.K) at raw juice condition and 0.06 kW/(m^2.K) at jaggery condition (Hugot, 1986) during boiling of sugarcane juice in vertical flooded tube evaporator using low pressure steam. Pool boiling heat transfer coefficient is 4.089 to 12.59 kW/(m^2.K) for 0.7 to 1.3 kW$_h$ (Aldana *et al*., 2015), less than 100 kW/(m^2.K) (Madrid *et al*., 2016). Overall heat transfer coefficients reported by Hugot (1986) are used in simulation as these are more conservative.

5. Performance for Jaggery Making

Performance of jaggery making is estimated for developed Long Stroke Reciprocating Compressor capacity of 1.409 L/s at 720 rpm. Latent Heat Exchanger, LHE, is judiciously designed to maintain low temperature approach during water evaporation at jaggery condition.

5.1. Capacity of Latent Heat Exchanger

Capacity of prototype for jaggery making unit is 0.6 kg/h. Weighted average water evaporation rate is about 2.6 kg/h. Cane crushing rate for same flow rate of juice is 4.6 kg/h. Considering 20 h/d operation of prototype requires 92 kg/d cane crushing rate. Weighted average water evaporation rate is 52 kg/d and jaggery making rate is 12 kg/d.

5.2. Calculations

Total quantity of water to be evaporated is calculated using mass balance for concentration change from raw juice and jaggery concentration. Concentration of raw juice, c_{rj} is 20°Brix and of jaggery, c_{jg} 90°Brix. Mass of water evaporated from 20 to 90°Brix is calculated using mass balance equation,

$$m_{tot.w.evp} = m_{rj}\left(1 - \frac{c_{rj}}{c_{jg}}\right) \quad \ldots (1)$$

Performance of VRCS is determined by assuming, water is evaporated in equal quantity, in eight stages, $n_{stg} = 8$. Quantity of jaggery produced by evaporation of water, m_{jg},

$$m_{jg} = m_{rj} - m_{tot.evp.w} \quad \ldots (2)$$

Concentration at outlet of nth stage by evaporation of water is determined using concentration balance,

$$c_{jc.stg.n.o} = \frac{c_{jc.stg.n.i}}{\left(1 - \frac{m_{w.evp.stg.n}}{m_{rj}}\right)} \quad \ldots (3)$$

Boiling point elevation, $dt_{bpe.jc.stg.n.o}$, calculated using Hugot (1986) formula,

$$dt_{bpe.jc.stg.n.av} = \frac{2c_{jc.stg.n.o}}{100 - 2c_{jc.stg.n.o}} \quad \ldots (4)$$

Temperature of juice at stage n, $t_{jc.stg.n}$,

$$t_{jc.stg.n} = t_{cnd} - dt_{app.he.stg.n} \quad \ldots (5)$$

Saturation temperature of water at stage n, $t_{sat.w.stg.n}$,

$t_{sat.w.stg.n} = t_{w.stg.n} - dt_{bpe.jc.stg.n}$ using this corresponding saturation pressure was found

Volumetric efficiency is estimated using total clearance volume, η_{vol},

$$vol_{4.exp} = vol_{3.cl.cyl} \cdot PR_{cmp}^{\frac{\gamma-1}{\gamma}} \quad \ldots (6)$$

$$\eta_{vol} = \frac{vol_{eff.swp}}{vol_{tot.cyl}} \quad \ldots (7)$$

Temperature approach for heat exchange, $dt_{1a.stg.n.cal}$, is calculated as follow,

$$dt_{1a.stg.n.cal} = \frac{Q_{w.v.cmp.1}}{U_{o.he.stg.n} \cdot A_{he.stg.n}} \quad \ldots (8)$$

$dt_{he.stg.n.assume} = dt_{he.stg.n.cal}$, if this condition satisfied, following parameters were calculated.

Time required for first stage evaporation

$$time_{req.evp.stg.n} = m_{w.evp.p.s} / mf_{w.v.cmp.n} \quad \dots (9)$$

Specific Moisture Extraction Rate,

$$SMER_{stg.n} = mf_{w.v.cmp.n} / W_{cmp} \quad \dots (10)$$

Specific work of compressor,

$$W_{sp.cmp.w.stg.n} = W_{cmp} / mf_{w.v.cmp.n} \quad \dots (11)$$

Each parameter is weighted with mass flow of water to estimate average parameters for different stages.

5.3. Flow chart of simulation

Performance of jaggery making is predicted using the MathCAD program as shown in figure 8.

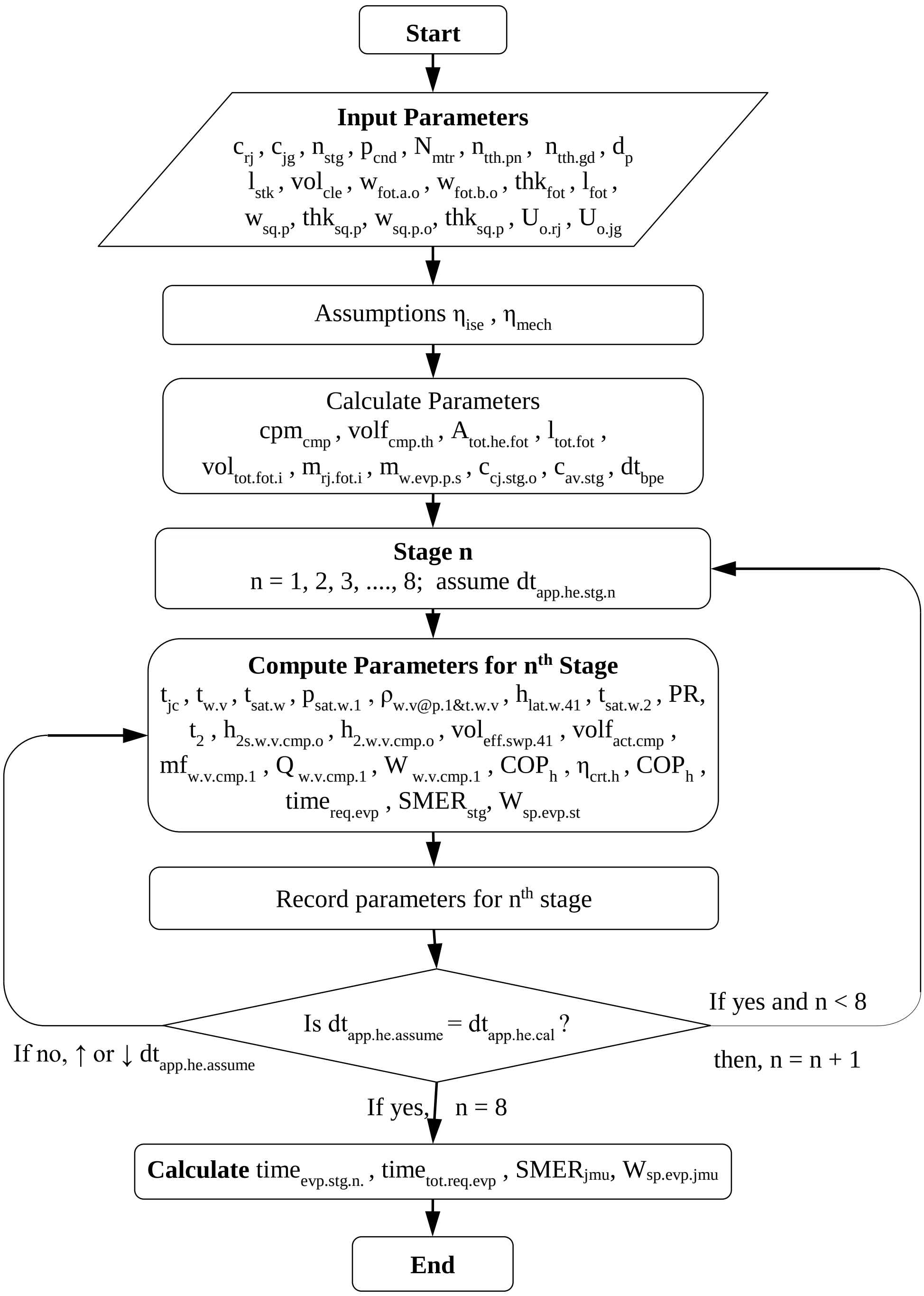

Figure 8: Flow Diagram for Performance of VRCS

6. Results and Discussions

Isothermal compression enhances the volumetric efficiency in conventional compressors. In case of Long Stroke Reciprocating Compressor for jaggery making, discharge pressure is limited to atmospheric

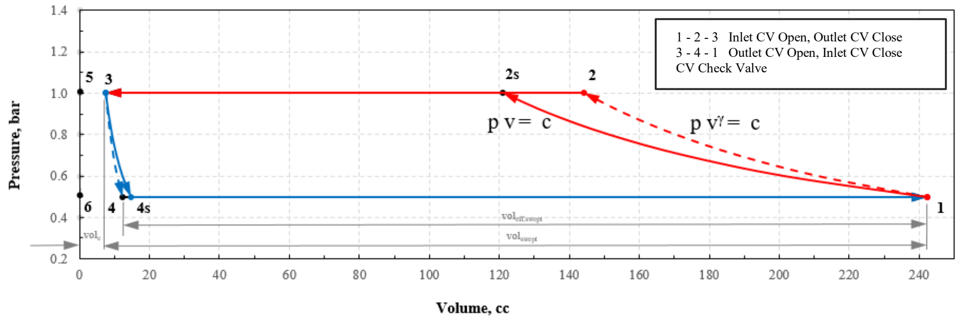

Figure 9: Theoretical p-V Diagram for Reciprocating Cylinder

pressure and suction pressure is determined by boiling point elevation and approach for heat exchange. Once the water vapour pressure in evaporator reaches the discharge pressure, outlet valve get opened and discharge pressure is maintained throughout the piston travel. Volumetric efficiency is 93.9% for suction pressure of 0.5 bar. Clearance volume is 7.36 cc. Total cylinder volume 242.2 cc reduces to effective swept volume 227.5 cc, as shown in figure 9.

6.1. Stress and strain analysis

Stress and strain were simulated in SolidWorks. Maximum force is 200 N. Maximum stress in pinion is 10.7 MPa at fillet between spur gear and shaft, as shown in figure 10. Maximum allowable stress is 144 MPa for mild steel. Design safety factor is 13.5. Maximum deflection is 1 micron at addendum circle, as shown in figure 11. Maximum stress in rack assembly is 1.9 MPa at rolling contact of bearing, as shown in figure 12. Factor of safety is 74.8. Maximum deflection in rack assembly is 1 micron in rack. It is tolerable in gears.

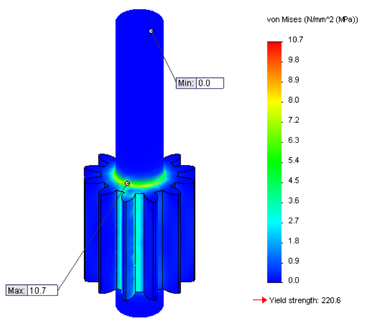

Figure 10: Max Stress 10.7 MPa in Pinion

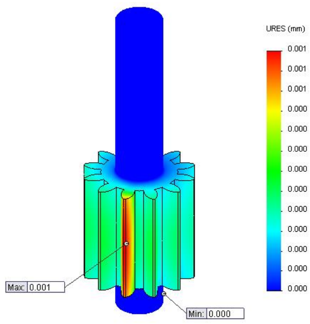

Figure 11: Max Deflection 1 micron in Pinion

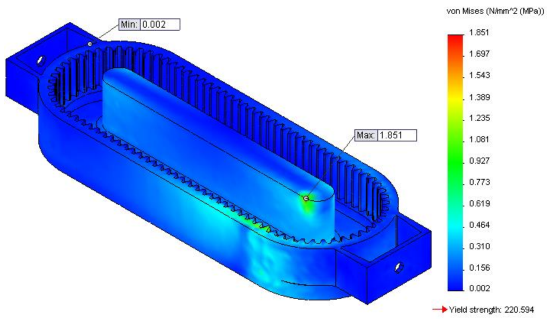

Figure 12: Max Stress 1.9 MPa at Rolling Contact in Pinion Guide

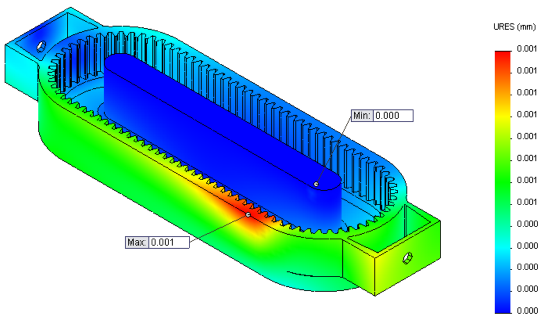

Figure 13: Max Deflection 1 micron at Rolling Contact on Pinion Guide

Factor of safety for pinion is 13.5 and for pinion guide is 74.8 for mild steel as material of construction. Deflections are tolerable. Hence, design of gear drive is very strong and safe.

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6.2. Free Run Test of LSRC

Free run test of Long Stroke Reciprocating Compressor has been conducted to measure the power required to overcome the friction between piston and cylinders-two sets, pinion and semi-circular gears/racks as well as velocity head loss during back and forth motion of pistons. Inlet and outlet ports of both cylinders were kept open. This gives the minimum power required to run the compressor at desired speed. Starting power requirement is 0.067 kW at 160 rpm. Power required to run the LSRC with open inlet and outlet ports is 0.270 kW at 752.1 rpm of motor. Figure 14 shows that frictional power increases linearly as speed increases. Oscillations of LSRC were observed after 447.3 rpm. Free run power requirement at 720 rpm is 0.255 kW. Compressor power varies during jaggery making by evaporating water. It is due to variation in boiling point variation and heat transfer coefficient.

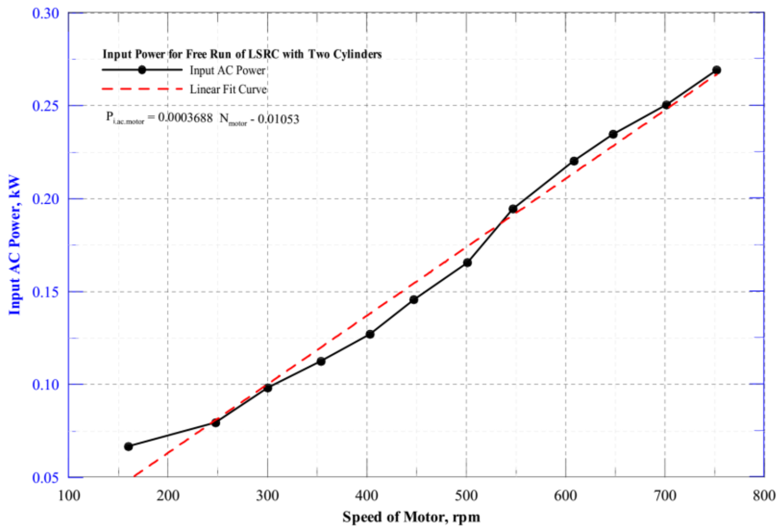

Figure 14: Free Run Input AC Power at Different Speed of Motor

Evaporator pressure reduces from 1.013 bar to 0.36 bar as shown in figure 15. Total water removal is equally divided in eight stages. Stages 6, 7 and 8 are further divided into 2, 2 and 4 equal parts respectively, as the concentration change is high. Theoretical performance of VRCS is estimated for

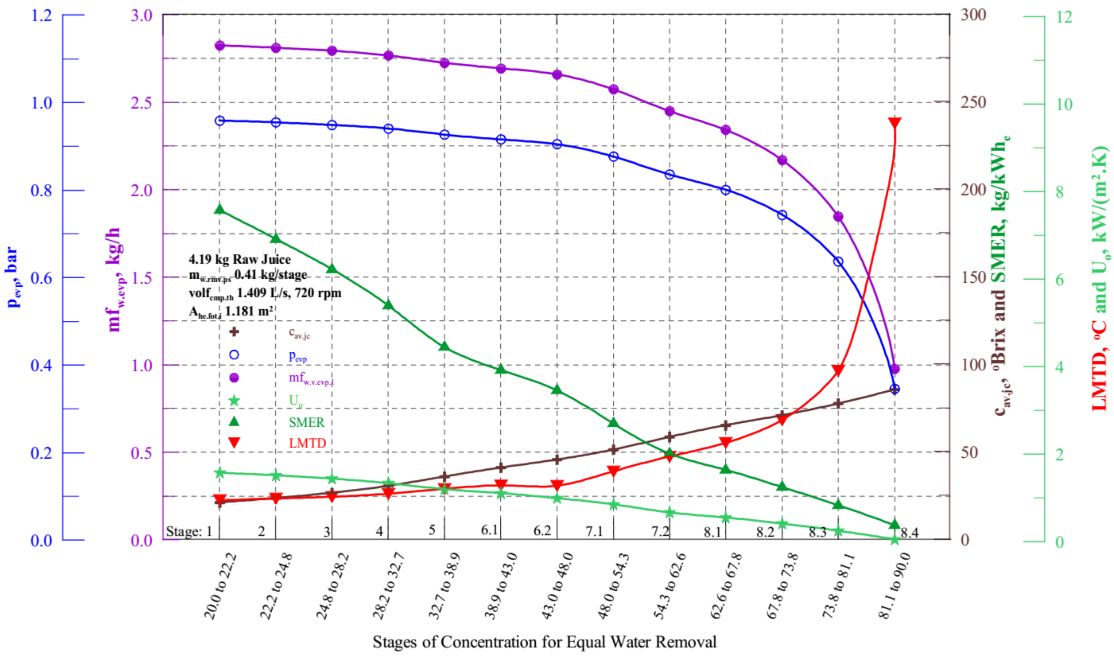

Figure 15: Performance Parameters of VRCS

each stage and then mass flow weighted average of each parameter is calculated. Compressor capacity reduces from 1.406 to 1.322 L/s. Specific energy consumption is 8.2 kWh_e/m^3 water removal. SMER is 122 kg/kWh_e. COP_h is 78 for 20 to 90°Brix concentration change. Total time required for jaggery making is 1 hour 18 min. Power requirement is 28.8 W for 2.62 kg/h water removal rate. Jaggery making rate is 0.6 kg/h. Experimental performance of VRCS will be tested for evaporation of water and then for sugarcane juice concentration. Considering, dry mode power consumption, actual power consumption is 0.284 kW, specific energy consumption is 108.3 kWh_e/m^3 water removal and SMER is 9.3 kg/kWh_e.

7. Conclusions

Novel Long stroke reciprocating drive has been developed with 292 mm stroke and bore 32 mm. Stroke to bore ratio is 9.125. It is successfully tested for operational stability of components. Flexible shaft is the crucial component in power transmission from BLDC motor to the piston through pinion of gear drive. Novel Long Stroke Reciprocating Compressor has been analysed for jaggery making while avoiding burning of bagasse for concentrating juice. Surface temperature of condenser tube is limited to 100°C by maintaining discharge pressure to atmospheric pressure. Hence, juice temperature is always less than 100°C. It reduces the caramelization of sugar and improves quality of jaggery. Theoretical specific energy consumption is 8.2 kWh_e/m^3 of water. Actual specific energy consumption of compressor is 108.3 kWh_e/m^3 of water removed for jaggery making, considering free run power. It eliminates bagasse firing and relives operators from strenuous environmental conditions. Saved bagasse can be composted on farm. It increases fertility of soil by increasing carbon content and sugarcane production gets significantly improved. Hence, LSRC is promising development in modernization of jaggery making for energy efficient vapour recompression. In future, next version of Long Stroke Gear Drive will be designed with lower tolerances to reduce frictional power and it will improve SMER.

Acknowledgements

This work was funded by Tata Centre for Technology and Design, IIT Bombay, Mumbai, India through grant # TCTD/DON/2015/125835. Support of Tata Centre for Technology and Design, IIT Bombay is gratefully acknowledged.

Nomenclature

Abbreviations		cpm	cycle per minute	PR	pressure ratio	tth	teeth, #	t	temperature, °C	v	velocity, m/s
c	concentration, °Brix	CV	check valve	mf	mass flow rate, kg/s	Q	heat duty, kW	thk	thickness, mm	volf	volumetric flow, m^3/s
COP	Coefficient of Performance	d	diameter, mm	p	pressure, bar	stk	stroke, mm	U	overall heat transfer coefficient, $W/(m^2.K)$	W	power, kW
Subscripts		cj	concentrated juice	evp	evaporator	jc	juice	o	outlet	sq	square
act	actual	cle	clearance	gd	gear drive	jg	jaggery	pn	pinion	stg	stage
amb	ambient	cmp	compressor	h	heating	jmu	jaggery making unit	req	required	swp	swept
app	approach	cnd	condenser	he	heat exchange	lat	latent	rj	raw juice	tot	total
c	cooling	cw	cold water	i	inlet	mech	mechanical	sat	saturated	v	vapour
cal	calculated	eff	effective	ise	isentropic	mtr	motor	sp	specific	w	water
Greek Letters		η	efficiency, %	ρ	density, kg/m^3	γ	adiabatic index				

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