How Servomotor Saves Power

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Apart from plastic material, electricity is the biggest cost component in injection moulding. It is necessary to save power. (Power is the rate of generation or consumption of energy but power and energy are used interchangeably where the time element does not matter).

The nature of power saving
Motion like mould clamping and injection has to be powered, so does heating of the material through the barrel. To reduce power consumption, the only way is to reduce waste. Let us first review the two laws of thermodynamics.

The First law of Thermodynamics
The First law of Thermodynamics is the conservation of energy. In energy conversion, energy is changed from one form to another. The energy before and after conversion is the same. Energy is neither created nor destroyed.

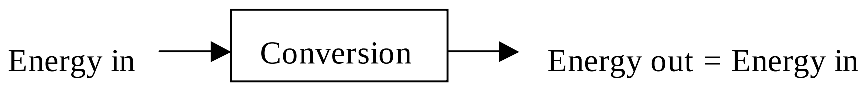

Fig. 1

During the conversion, ‘useful’ energy out is less than energy in as during conversion, ‘useless’ energy is also produced.

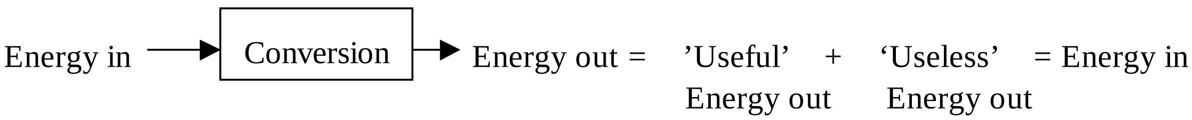

Fig. 2

The Second law of Thermodynamics
The Second law of Thermodynamics says in an energy conversion, entropy can only increase, but cannot decrease. Entropy is a difficult concept to explain in a few statements. For the purpose of this discussion, the Second Law can be simplified to read ‘useless’ energy out is heat energy.

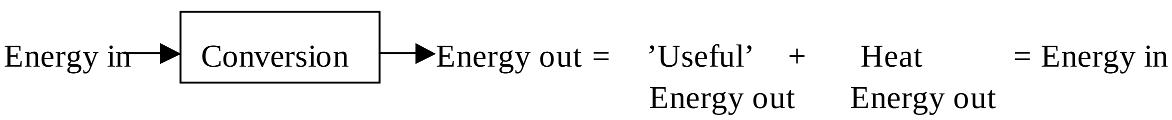

Fig. 3

Asynchronous motor

The traditional motor used in an injection moulding machine is the asynchronous (squirrel cage) motor. It drives the pump. The stator of the asynchronous motor generates a rotating magnetic field when powered by three-phase electricity. For a 4-pole stator driven by 50 Hz power, the magnetic field rotates at 1500 rpm.

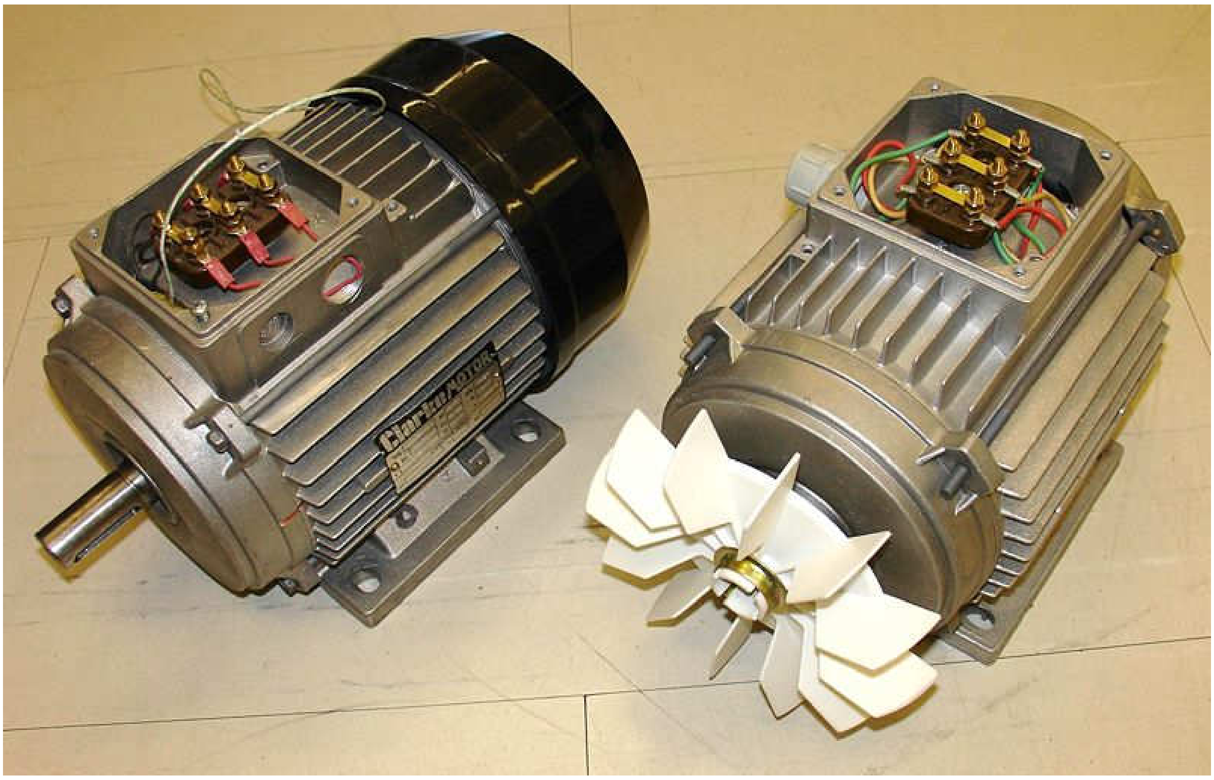

Fig.4 Asynchronous motor and fan

The rotor has many copper bars in a slanted position. Their ends are short circuited together at each end. As a result, the rotor looks like a squirrel cage. Under the influence of a rotating magnetic field , current is induced on the copper bars. The interaction of the currents and the magnetic field generates a torque to turn the rotor. The rotor speed is from 20 to 60 rpm slower than the rotating magnetic field which is why the motor is called asynchronous (not the same speed).

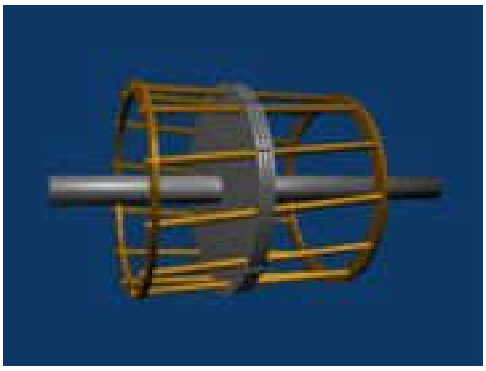

Fig.5 Squirrel cage (showing copper bars and three silicon steel plates)

Two types of silicon steel plates are stacked up to support the rotor copper bars and the coils of the stator respectively.

Fig.6 Rotor and stator silicon steel plates and a rotor

An asynchronous motor converts electrical power to mechanical power. In the conversion process, due to the resistance of the coil, eddy current in the silicon steel plates and friction at the bearings, the ‘useful’ output power is only about 90% of the input power (at full load). The remaining power turns to heat. The reason a fan is attached to the rotor is to remove the heat generated to avoid overheating the motor.

An asynchronous motor can be overloaded two times for a brief period. When overloaded, the current increases so the heat generated also increases. Without the proper overload protection, the coil could be burnt.

Hydraulic pump

A hydraulic pump converts rotational power to fluid power (pressure and flow). The friction in the pump reduces the output pressure. There is also internal leakage which reduces the output flow. As a result, the ’useful’ output power is less than the input rotary power. The wasted power turns into heat that raises the oil temperature. This is a reason why an oil cooler is installed in an injection moulding machine.

Hydraulic motor and cylinder

A hydraulic motor or cylinder turns fluid power back to rotary power or linear motion power respectively, in order to turn the screw or to do injection. Like the hydraulic pump, heat is generated in the conversion which raises the oil temperature.

Pipes and hoses

Hydraulic oil flows in pipes and hoses and turns at elbows (fittings). The friction with the pipe wall and within the hydraulic oil itself reduces pressure and generates heat. Low-cost injection moulding machines use narrow pipes, hoses and fittings to reduce cost, but the flow speed is increased as a result. The frictional loss will increase and the oil temperature would rise higher. More energy is lost this way.

Why fixed displacement pump wastes power?

When a constant rotary speed asynchronous motor drives a fixed displacement pump, the pump outputs a constant flow rate. However, the various motions in an injection moulding cycle require different flow rates, e.g. mould open, mould close, ejection, plasticize, inject and holding pressure, even idle time. The oil flow not needed by the motion flows back to the oil tank at the pressure set at that time. The slower is the required motion, the more oil flows back to the oil tank and so the waste is more. Similarly, the higher is the pressure, the more is the power that is wasted. The wasted power turns into heat to raise the oil temperature.

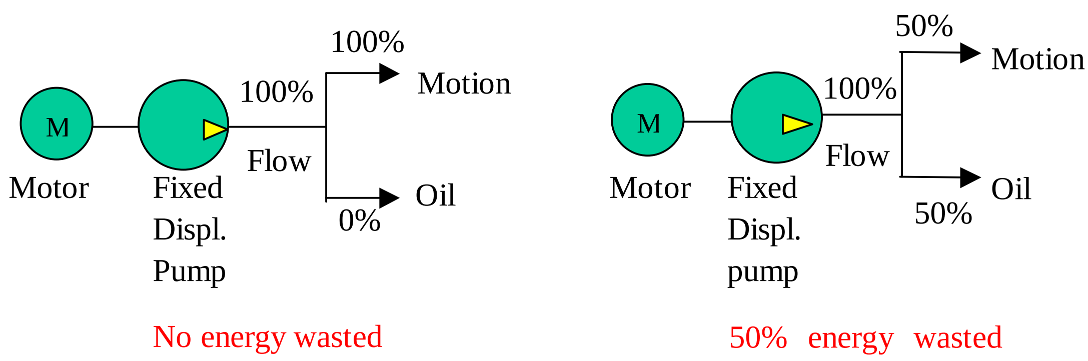

Fig.7

In an injection moulding cycle, the flow requirement during hold pressure is very low, as the screw only inches forward slightly to compensate for the part shrinkage when they cool. The flow is estimated to be less than 5% so more than 95% of the oil returns to the oil tank at holding pressure. The thicker is the wall of the part, the longer is the holding pressure time, the more is the energy wasted. From another viewpoint, the potential to save energy is more, or the payback period of energy-saving investment is shorter.

In general, when the flow is far from the maximum flow, the motion takes a long time and the pressure is high, the potential saving is higher.

How variable displacement pump changes flow?

From the above, the key to energy saving is to be able to change the pump flow rate. A variable displacement pump can supply from zero to maximum flow rate under the drive of a constant speed asynchronous motor.

The most common variable displacement pump is the axial piston pump. When the swash plate angle is zero, the flow rate is zero. When the swash plate angle is maximum, the flow rate is maximum. According to the angle of the swash plate, flow rate could be varied.

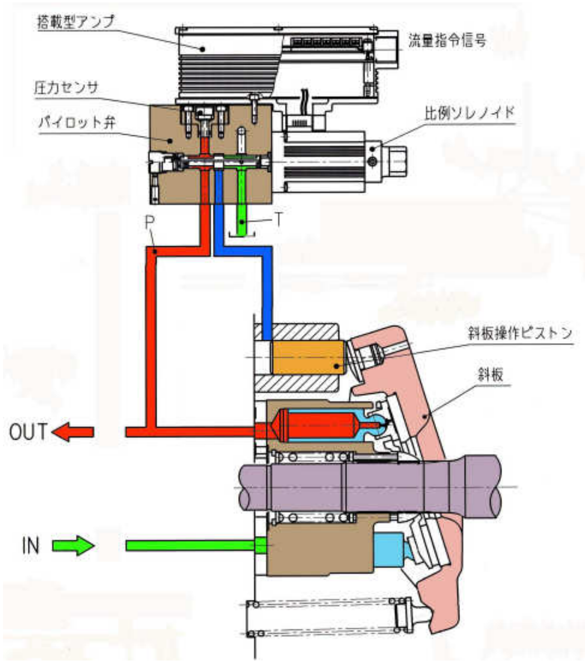

Fig. 8　　Axial piston (variable displacement) pump

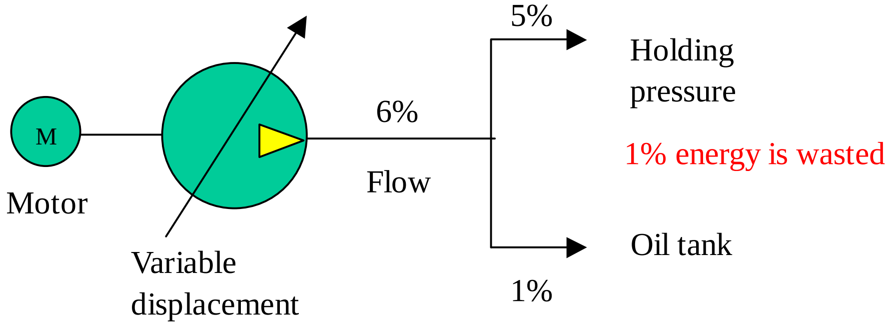

Fig.9

How an inverter changes flow rate?

An inverter changes the power frequency to drive the asynchronous motor. The supply frequency at 50 Hz is changed to between 5 and 50 Hz so the asynchronous motor speed changes from 10% to 100% (full speed). Coupled with a fixed displacement pump, the flow rate varies from 10% to 100%.

The inverter is a piece of high current electronic equipment which itself consumes power. As a result, the power saving ability is less than that of a variable displacement pump.

An asynchronous motor was designed for constant rotational speed so its rotor inertia was not optimized to variable speed. If every speed up and slow down takes 0.1 s, the cycle time would be increased by 2 s as there are about 20 speed changes in a cycle. Users of inverters have observed reduced production rate, which further reduces the attractiveness of this scheme.

The vane pump is the most common fixed displacement pump. Vane pump depends on centrifugal force to press the vanes against the pump cartridge to do the sealing, so oil could be pumped out at high pressure. When the rotor speed is reduced, so does centrifugal force. The internal leakage will increase and the (volumetric) efficiency of the pump is reduced (at low flow rate).

In fact, inverter is only used when retrofitting an old injection moulding machine to save power. The reason is it is much easier change wiring then to replace a fixed displacement pump with a variable displacement pump on-site. When buying a new machine, customers would not specify one with an inverter and a fixed displacement pump.

Servomotor

A servomotor was optimized for speed up and slow down. How does a servomotor maintains its torque while reducing its rotor inertia? It depends the physics of matter as described by the following equations. $\propto$ is a mathematical symbol to denote ‘is directly proportional to”.

Torque $\propto$ Rotor diameter (Linear proportion)

Inertia $\propto$ (Rotor diameter)^2 (Square proportion)

Torque $\propto$ Rotor length (Linear proportion)

Square proportion rises faster than linear proportion. If the rotor diameter increases by 20%, (rotor diameter)^2 increases by 44% ($1.2^2 = 1.44$).

Servomotor uses a small diameter rotor to reduce inertia. The rotor length is increased to compensate for the reduced torque. The outlook of a servomotor is clearly longer and has a smaller diameter than an asynchronous motor of the same power.

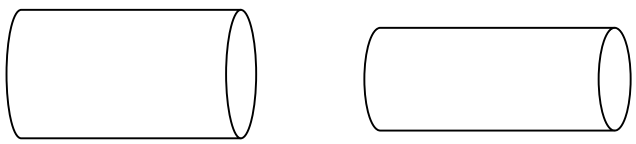

Fig.10

A certain Japanese supplier uses neodymium (a rare earth element) magnet to create the magnetic field. It is much stronger then ferrite magnet so torque is increased. The same supplier also uses reluctance torque to get extra torque.

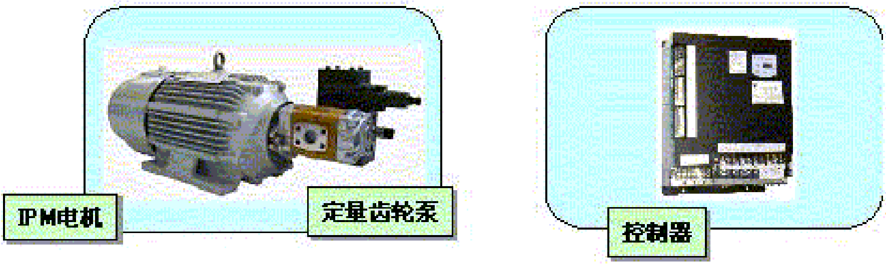

Fig.11 Daikin IPM motor and controller

The use of permanent magnet to create the magnetic field has a higher efficiency than induction magnetic field, as the copper loss and eddy current loss are avoided.

To get to 2000 rpm from 0 rpm, it only takes 0.05 s. As a result, a servomotor driving a pump, the cycle time slow down is observed only when it is less than 5 s.

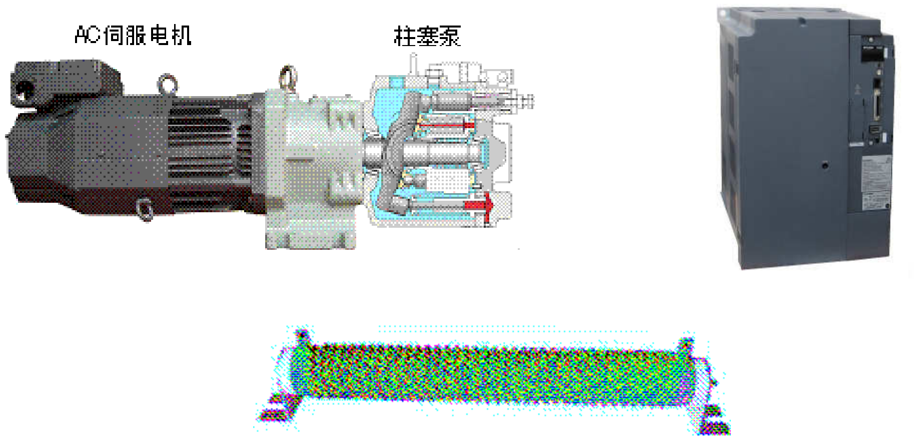

Fig.12 Yuken motor, variable displacement pump, controller and braking resistor

When a servomotor brakes, it becomes a generator which drives a bank of braking resistors to which the kinetic energy is dumped. Heat is generated and get dissipated into the atmosphere. A Swiss injection moulding machine manufacturer actually stores the braking power of a fully electric machine in a battery to be released later to drive the servomotor. This epitomizes the nature of energy saving: use extra investment to save energy (recycle energy is more appropriate here).

Fully electric machine

The energy-saving feature of a fully electric injection moulding machine is well-known. A fully electric machine also uses servomotors, but at least four of them to drive injection, plasticizing, mould opening/closing and ejection. The remaining motions like core pull/unscrewing, carriage motion and mould height adjustment could be driven by servomotors or cheaper motors.

In direct drive, a ball screw or a toggle arm converts rotary power into linear power. Alternatively, a belt or a gearbox converts high speed rotation to low speed rotation power.

When a servomotor drives a pump, oil flows through pipes and hoses to reach a hydraulic cylinder or motor, where energy is converted back to motion. When compared to a fully electric machine, direct drive saves two conversion processes. The energy saved is estimated at 10%. The full comparison of the two drives is shown in the table below.

	Fully electric machine	**Servomotor driving a pump**
Number of servomotors	⩾ 4	1
Cost	Very high	High
Maintenance cost	Very high	High
Parallel motion	Yes	No
Power saving vs servomotor driving a pump	About 10%	—
Oil leakage?	No	Possible

Table 1

Idle state
After an injection moulding machine is turned on but before there is any motion, the machine is in idle state.

In the following situations, the machine is also in idle state.

1. When cooling time is longer than plasticizing time, the machine is in idle state during the excess time. The bigger is the wall thickness of the part, the longer is the idle time.

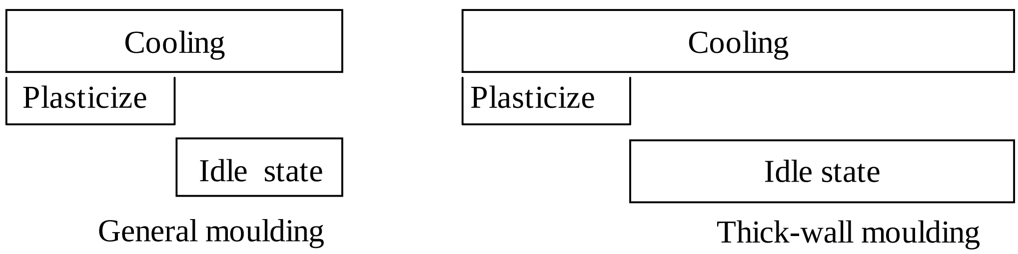

Fig.13

2. When a robot arm is removing the parts
3. During semi-automatic operation when the operator opens the front gate to remove the parts or to do inserts.

At idle state, an asynchronous motor driving a variable displacement pump turns at a fixed speed of about 1460 rpm but there is no flow. We measured 7 A of current at an 11 kW motor during idle state. Compared to the full load power of this motor at 24 A, the idle current is 29%.

A servomotor driving a variable displacement pump is motionless at idle state. Any current used is only that of the controller. The current of an 11 kW servomotor at idle state is less than 1 A.

Oil temperature as an indicator
The ability of servomotor to save power could be revealed from the temperature of the hydraulic oil.

Using a 50-ton machine to make a single-cavity disposable cup (used on airplanes), in summer time in South China and the oil cooler has no cooling water circulation, the oil temperature is only 37 deg C.

Wasted energy is dumped, mostly to the oil. If oil temperature is an indicator of energy saving, a variable displacement pump driven by an asynchronous motor can hardly be compared to a servomotor.

Motor efficiency
Efficiency is output power divided by input power.

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}}$$

Input power to a motor is the consumed electrical power.

Output electrical power of a motor is the (provided) rotational power.

In the ideal lossless situation, output power is the same as input power, so efficiency is 100%. In the real world, output power is less and balance turned into heat. Refer to the section of the Second Law of Thermodynamics.

Asynchronous motor has an efficiency of about 90% at nominal load, but at load below 50%, the efficiency drops dramatically. This is the reason for the 29% current consumption at idle state mentioned before.

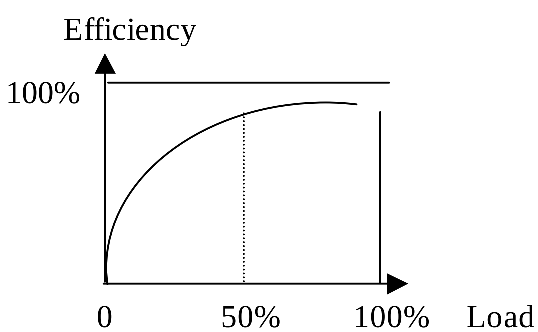

Fig.14

A British company supplied a device called Powerboss which reduces the supplied voltage to an asynchronous motor during periods of low load. The principle is to reduce the current to reduce the magnetic flux in order to reduce the copper loss (waste). To be noted is the motor rotational speed is not changed so the injection moulding cycle time is not affected.

The servomotor efficiency is like Fig. 14 but the efficiency is higher, especially during low rotation speed. In the following drawing, the red lines show the power consumption of an 11 kW asynchronous motor driving an A56 variable displacement pump; the blue lines show the power consumption of an 11 kW servomotor driving the same A56 pump, at various flow rates and loads.

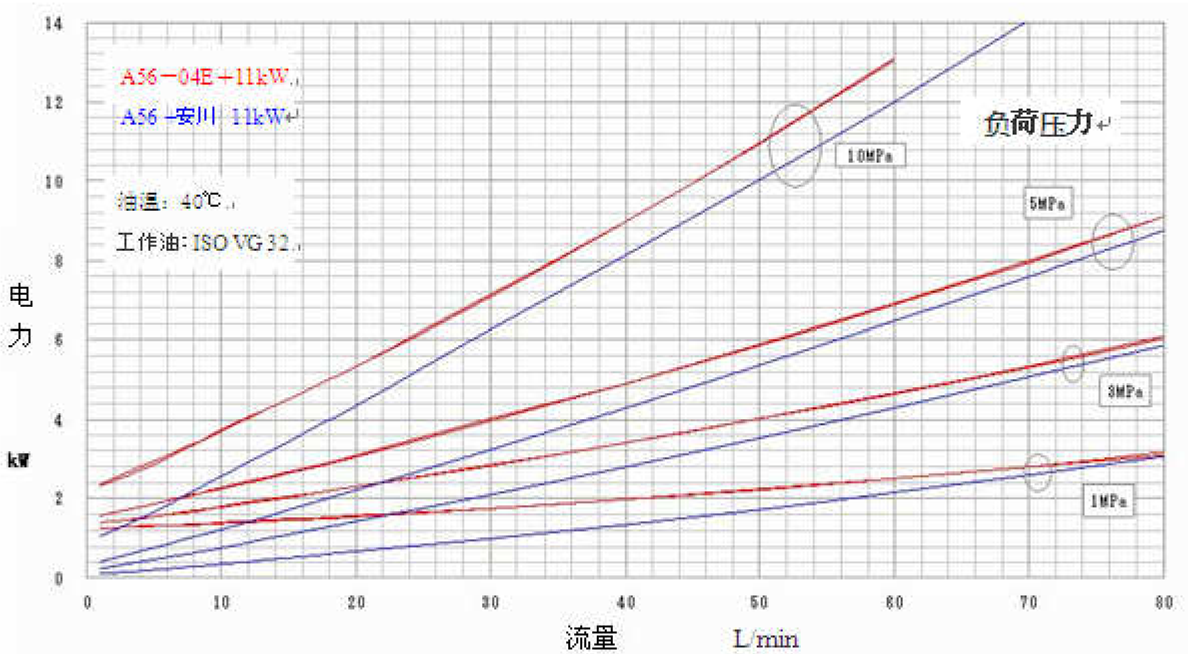

Fig.15

How much power could be saved?

According to a servomotor supplier, a servomotor driving a pump could save 60% of the power of a fixed displacement pump machine, and 40% of the power of a variable displacement pump machine.

Another supplier quoted a figure of more than 50% saving without mentioning the type of pump.

Actually how much power could be saved depends on the wall thickness of the parts, and whether the mould uses cold runner. The holding pressure time and idle state duration both have their contributions. There is no fixed percentage in power saving.

In general, the bigger is the wall thickness, the higher is the potential for servomotor to save. With big wall thickness, the holding pressure time is long, so is idle time. PET preforms belong to this category. If the cold runner diameter is bigger than wall thickness, the holding pressure time and idle time are determined by the cold runner.

On the other hand, thin-wall parts (in a hot runner mould) have short holding pressure time, even zero. Similarly, cooling time is also zero. The potential for energy saving by servomotor is limited. In fact, Tat Ming recommends for parts with cycle time at 5 s or less, like making thin-wall (0.5 mm) food containers, asynchronous motor driving a fixed displacement pump be used so as not to lengthen the cycle time which would have been incurred when servomotor speeds up and slows down.

For parts with cycle time between 5 and 8 s cycle time, an asynchronous motor driving a variable displacement pump could be used.

For parts with cycle time above 8 s, when cooling time is longer than plasticizing time, when injection time is more than 3 s, when screw rotation speed is less than 70%, when a robot arm is used to pick the parts, when semi-automatic mode is used, Powerboss or servomotor could be used.

Cycle time	Other conditions	Recommendation
< 5 s	Thin-wall（< 0.5 mm）	Asynchronous motor driving fixed displacement pump
5 – 8 s	—	Asynchronous motor driving variable displacement pump
> 8 s	Thick-wall Cooling time>plasticizing time Injection > 3 s Screw rotation speed < 70 % Robot arm used Semi-automatic mode	Asynchronous motor driving variable displacement pump+Powerboss or Servomotor

Table 2

Gear pump vs. piston pump

The question to ask is whether the servomotor should drive a fixed or a variable displacement pump.

The most common fixed displacement pump used in injection moulding machine is vane pump. As mentioned before, it is not suited to variable speed control as the increased leakage at low speed reduces its (volumetric) efficiency.

The most common pumps used with a servomotor are fixed displacement gear pump and variable displacement axial piston pump.

The volumetric efficiency of gear pump is below 90%. It has a simple construction, cost is not high, noise is not high and is very tolerant to contaminated oil.

Axial piston pump has a volumetric efficiency of about 95%. It has a precise construction and so is not very tolerant to contamination. Furthermore, it is a bit noisier than gear pump. However, its variable displacement feature could reduce the torque load on the servomotor, so its current and heat up are reduced. This is utilized during holding pressure time when the flow rate is very low so the holding pressure time could be longer without overheating the servomotor. The dual displacement option of Yuken servomotor/pump is capable of this feature. Despite the fact that a variable displacement pump allows many different displacements, only a high displacement and a low displacement are used in Yuken's offer.

From the diagram below, both holding pressure and lockup use low flow rate but high pressure. During these two motions, the pump displacement is switched to low to reduce the torque load to the servomotor which heats up due to large current when rotating slowly. Even fully electric machine cannot use this feature to reduce heat up. If dual displacement is not used, these two points will fall out of the P-Q range of the pump (at high displacement), but are still within the overload region as marked by the dotted line. Short overload durations are allowed in the overload region.

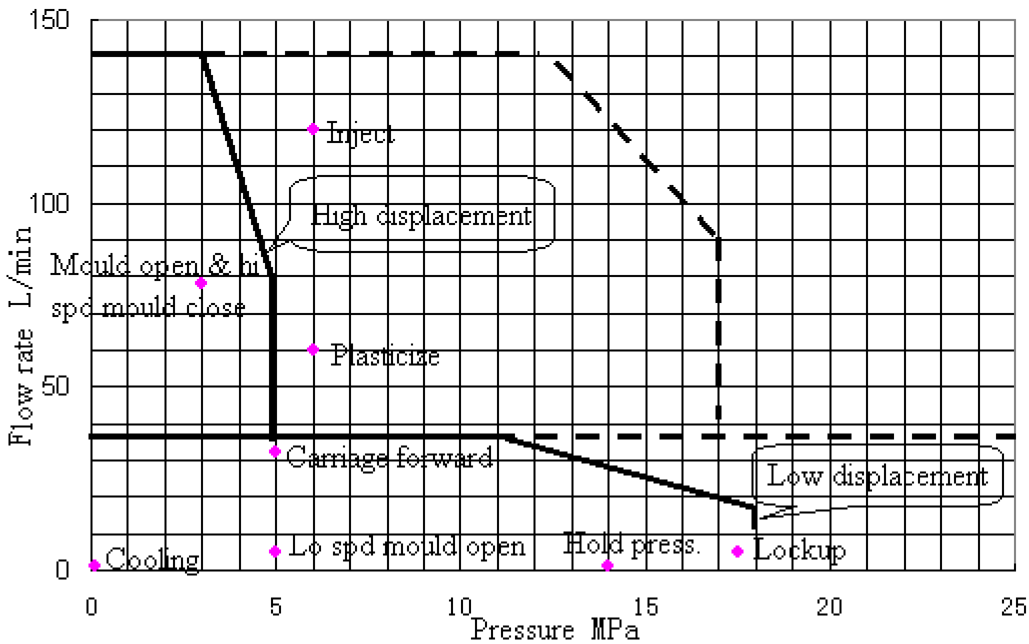

Fig.16

If the lockup is done by a toggle, the lockup duration is by nature short. If a direct hydraulic clamp is used and a check valve is not used to maintain the lockup pressure, the servomotor has to work over the whole clamping duration. The low displacement feature could be turned on to provide an extended holding pressure and lockup duration without overheating the servomotor. This is because at low displacement, the servomotor speed can be increased to keep the same (low) flow rate.

Limitations of servomotor

At low rotation speed, the counter e.m.f. (electromotive force) generated in a servomotor is less than that at high rotational speed. The resultant increased current could overheat the coils. This will happen during the long holding pressure period. The dual displacement Yuken servomotor/pump maintains the servomotor at a high rotational speed to reduce the heat up.

When buying a machine powered by a servomotor, care must be taken to see whether the motor power is too low which can only maintain a short holding pressure time.

A big injection moulding machine requires a big servomotor to drive it, but a big servomotor also has a big rotor inertia so it cannot meet the 0 to 2000 rpm in 0.05 s requirement. The two Japanese suppliers do not have offers higher than 15 kW.

Bigger injection moulding machines can only use two or more servomotors the pumps of which combine flow to do the driving. In this way, there is sufficient flow rate and the response is fast enough. A 3500-ton machine has been built driven by 10 servomotors/pumps.

Servomotor is expensive. Whether to adopt it is determined by the product (refer to an earlier section) and whether the machine used to make it now has a fixed or variable displacement pump. If the extra investment has a payment period of less than 2 years, the servomotor is worth considering.

Precision and other advantages

The rotor of a servomotor is fitted with an encoder. Together with the controller, closed loop control of rotor speed is accomplished. As injection speed is the real object of control, and rotor speed is only theoretically proportional to it, servomotor speed control is only semi-closed loop, but is already more precise than open loop control.

At the outlet of the servomotor driven pump is a pressure sensor. Together with the controller, pressure closed loop is accomplished. In this way, we say servomotor control provides 3/4-closed loop control (3/4=1/2*1/2+1/2*1).

Precise speed and pressure control are the necessary conditions for stable production. As the oil temperature is not high, temperature variation is also reduced. Precision is further improved. A low hydraulic oil temperature can reduce or eliminate oil cooling requirement.

Other advantages include low noise (especially during idle state), small volume and light weight.

Power saving in heating

Based on the same principle, to save power in the heating of the material through the barrel, the only way is to reduce waste.

The heat from band heaters pass through the barrel wall by conduction to reach the material inside the barrel. At the same time, heat is lost by radiation and convection to the surrounding. A barrel cover containing insulation wool can reduce the heat loss.

Fig. 17 A barrel cover with insulation wool inside

Some barrel covers are full of ventilation holes. Their purpose is to shield the operator from the much higher temperature of the barrel rather than to save heating power. Such barrel covers do allow the barrel temperature to go down faster when the set temperature is exceeded.

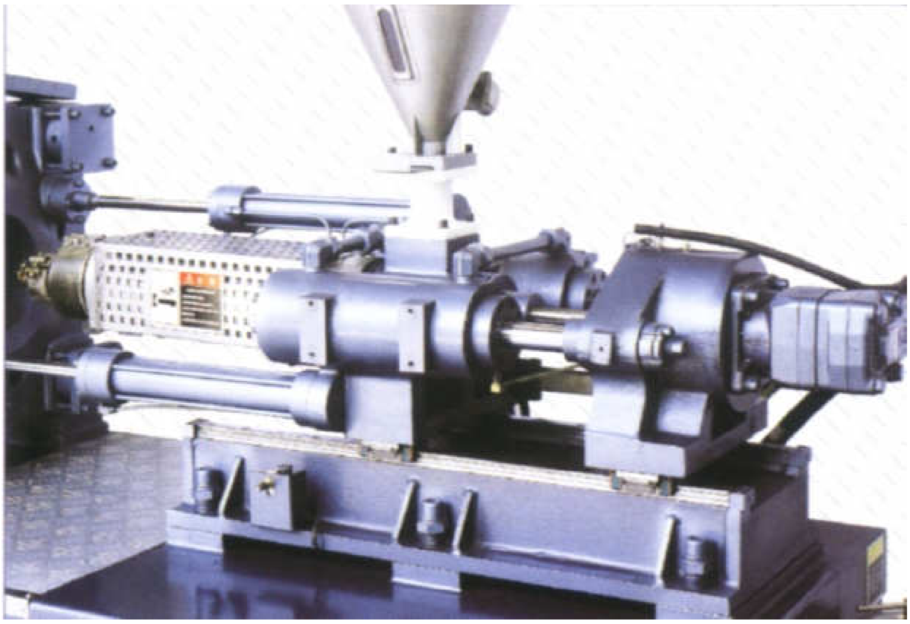

Fig. 18 A ventilated barrel cover

Power saving through operation

After a maintenance operation on band heaters or thermocouples, if the barrel cover is not immediately replaced, heat loss will occur.

In a factory installed with swinging fans, avoid the fans from blowing at the barrel covers. Otherwise, the increased convection not only wastes power, the material temperature is affected and so is product stability.

The temperature of the heater zone next to the water collar should not be set too high. This zone has an additional heat loss through conduction towards the cooling collar.

Revolution

After the injection moulding machine was invented, it went through a few evolutions.

The use of hydraulic power to replace human power was an advancement.

Fig. 19 The clamping unit is still manually operated

The early machines used a plunger to do the injection. The plasticizing is done by band heaters around the barrel helped by a torpedo inside the barrel.

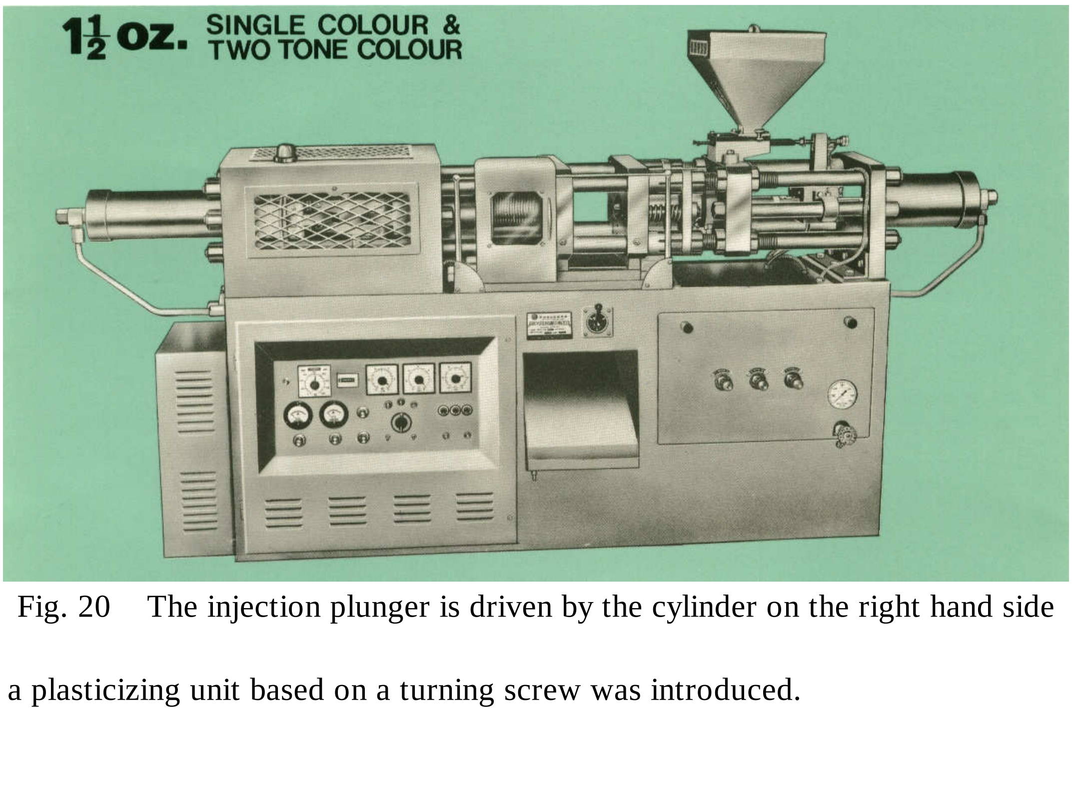

Fig. 20 The injection plunger is driven by the cylinder on the right hand side

Then a plasticizing unit based on a turning screw was introduced.

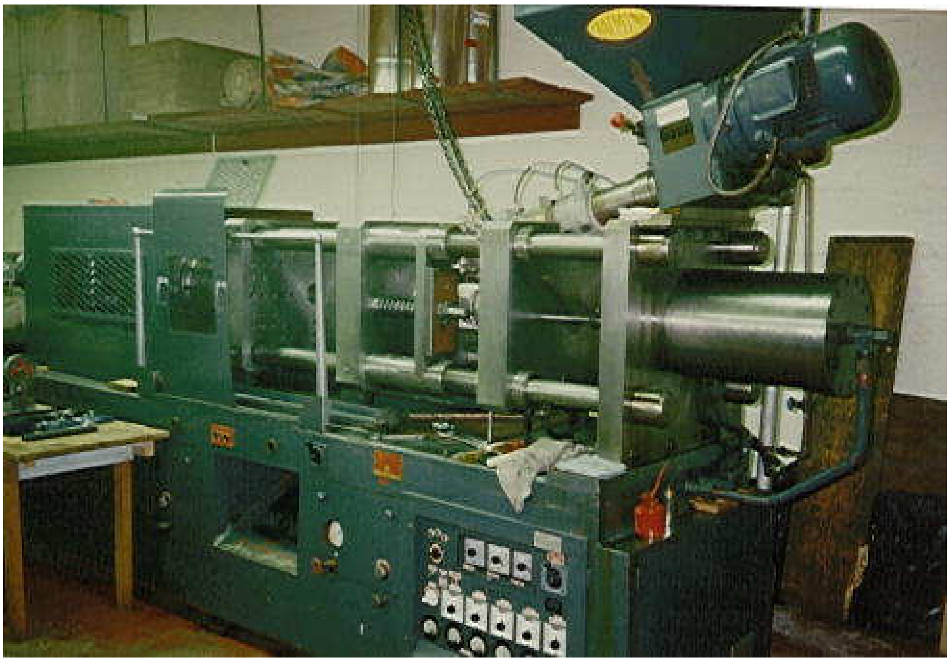

Fig. 21 The plasticizing unit is above the injection unit

The reciprocating screw integrated plasticizing and injection into one unit to reduce cost. The two units are in-line (not at an angle to each other).

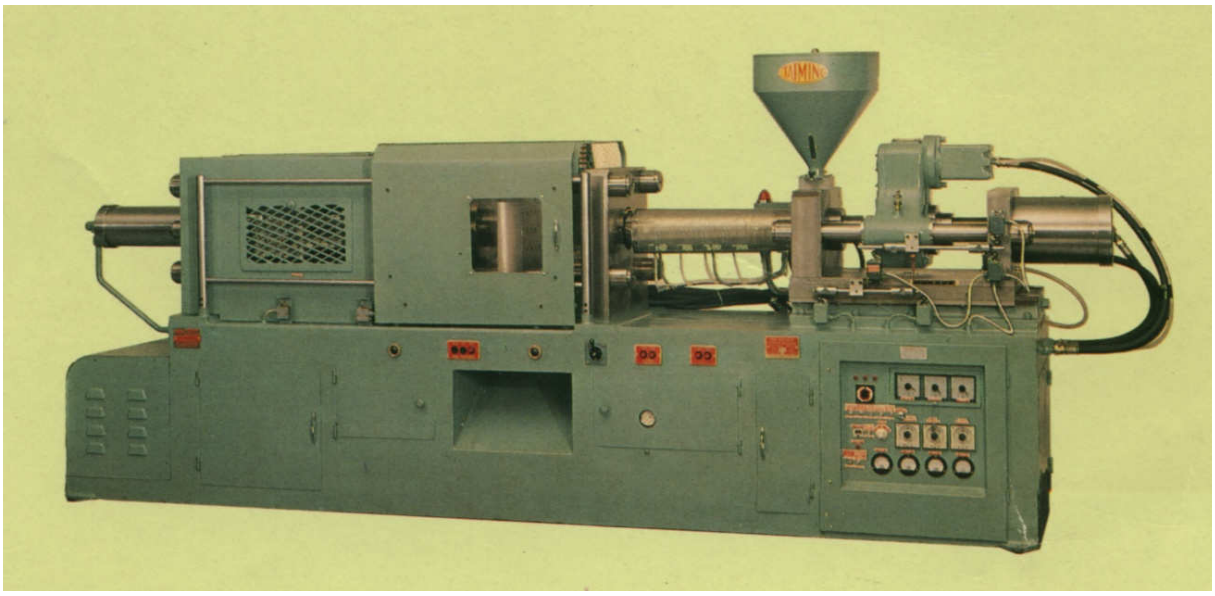

Fig. 22 The reciprocating screw is turned by a hydraulic motor and pushed by a hydraulic cylinder

Another innovation was the use of proportional pressure and flow valves. Their use was coupled with the introduction of the microprocessor to control the injection moulding machine. The hand set values of the valves do not have to be recorded for reuse next time. The machine also becomes more versatile.

Fig. 23 A microprocessor controlled machine

The wide-spread use of variable displacement pump ushered in the era of energy saving to counter the ever-rising cost of electricity.

The introduction of fully electric machine was a revolution. Since there is no more hydraulic oil the temperature of which could vary, the product stability took a quantum leap forward. Precision, parallel motion, energy-saving, reduced noise and no oil leakage are other improvements.

Fig. 24 A fully electric machine

The next innovation was the use of servomotor driving a pump. Most of the advantages of the fully electric machine are kept, including energy-saving, 3/4-closed loop control and reduced noise, but at a much lower price tag. We believe this is another revolution in the making.

Fig. 25 A servomotor-driven machine

Conclusion

The crux of energy saving is in reducing waste. When the injection moulding machine motion is less than full speed, reducing the pump flow can reduce waste. New technologies like variable displacement pump and servomotor can reduce pump flow rate.

Servomotor and asynchronous motor differ in the following ways which enable the former to be used in injection moulding with energy saving.

	Servomotor	**Asynchronous motor**
Design objective	Variable rotation speed	Constant rotation speed
Rotor inertia	Small	Big
Efficiency (low load)	Higher	Low
Efficiency (high load)	95%	90%

Table 3

During periods of low load (including idle state), asynchronous motor efficiency is low which creates waste. Asynchronous motor turns at a constant speed, but the speed of a servomotor could vary, so friction can be reduced at low rotation speed. During idle state, the servomotor even stops rotating.

Not all products are suited to be made by a servomotor-driven pump machine, just like not all products are suited to be made by a fully electric machine. There are areas where fixed displacement pump and variable displacement pump driven by asynchronous motor are suitable. The adoption of a technology is determined by its payback period.

The power saving in barrel heating and the training of the operator are also areas to look into as well.

We acknowledge Daikin, Yuken and Victor for their data and pictures.