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ORIGINAL ARTICLE

Optimizing energy savings of the injection molding process by using a cloud energy management system

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Abstract The injection molding (IM) process is a widely used manufacturing process for injecting material into a mold for producing a diverse array of parts. It includes several energy-consuming procedures, such as heating plastic pellets, forcing melted polymer into a mold cavity, and cooling down the molded products. In this study, developmental factors of IM machines and processes along with energy savings progress are reviewed. In addition to several machining factors and process parameter optimizations, applying an energy management system (EMS), as well as new tools to reduce energy consumption in the IM process, has the potential for great improvements in the long term. A cloud energy management system (CEMS), called the intelligent Energy Management Network (iEN), which was launched by Chunghwa Telecom, was installed on two IM machines to illustrate the optimization of energy savings by a variable-frequency drive (VFD) and process parameter optimization. Through the recorded process dynamics, the energy usage, and product quality of the IM process using the iEN, the energy savings could be analyzed by the expert, measurement and verification (M&V) systems on the software as a service (SaaS) platform. The electricity savings on the IM machine after installing a VFD were 41.3%. Further optimization by using the one-factor-at-a-time (OFAT) approach to measure the process parameters, such as melting temperature (310.0~350.0 °C), mold temperature (110.0~130.0 °C), and clamping force (120.0~160.0 T), was carried out. The experimental and analyzed results indicated that the optimal operating conditions were at a melting temperature of 330.0 °C, a mold temperature of 120.0 °C, and a clamping force of 140.0 T. Through the optimization procedure of the process parameters carried out by the iEN, further electricity savings of 12.2% were added. Therefore, the saved electricity cost and payback period of installing the VFD and the iEN were NT$ 26,363/month and within 4 months, respectively. The saved electricity and reduced carbon dioxide (CO_2) amounts were 107,200.5 kWh/year and 55,851.5 kg/year, respectively. Continuous analysis of the optimization process, energy savings, resource conservation, and waste reduction of the IM process using the iEN has shown overall benefits to the IM process, the machines, and the future decisions and designs regarding new products.

Keywords Injection molding (IM) process · Variable-frequency drive (VFD) · Cloud energy management system (CEMS) · intelligent Energy Management Network (iEN) · Energy savings · Optimization

Abbreviations

ANN	artificial neural network
CEMS	cloud energy management system
EMS	energy management system
GA	genetic algorithm
IaaS	infrastructure as a service

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iEN	intelligent energy management network
IM process	injection molding process
M&V systems	measurement and verification systems
OFAT	one factor at a time
PaaS	platform as a service
SaaS	software as a service
VLANs	virtual local area networks
VDP	variable-displacement pump
VFD	variable-frequency driver
VSD	variable-speed drive

Introduction

The injection molding (IM) process is a process whereby a material is injected into a mold for producing parts. It is a widely used manufacturing process for both prototyping and mass production of automobiles, household appliances, food and beverage packaging, plastic building materials, and electronic communications (Xu et al. 2015; Rusdi et al. 2016; Chen et al. 2016). Based on a market survey, the IM machine is the most crucial piece of plastic-processing machinery, accounting for 60–85% of the IM manufacturing in developed countries. Among them, China has recently become the world's largest producer and consumer of IM machines. From 2010 to 2016, China's IM machine sales increased from 20 billion to 30 billion RMB. In 2014, nearly 30%, a total of 25,802 IM machines made in China were exported (Dublin 2015).

During the IM process, plastic pellets are heated, and the melted polymer is forced into a mold cavity to produce "a part" with a unique shape. All the procedures of the IM process consume electricity: 17% of which is used for heating, 32% is used to drive the extruder/injection system, and 33% is used in temperature regulation (Godec et al. 2012). If the consumed energy of IM machines could be reduced or used more efficiently, the energy savings of IM machines worldwide would be a very significant amount. Generally speaking, energy consumption of the IM process is related to the machinery, part design, plastic material, production rate, mold design, and process parameters (Yin 2015). The developmental factors of IM machines and processes along with energy savings progress are reviewed in Table 1. The components of the machinery include the driving, injection, and clamping systems. The driving unit provides power for the injection and clamping units and is considered to be the primary energy consumer (Intelligent Energy-Europe 2006). Types of drive systems for IM machines vary and include conventional hydraulic drive systems, servo-driven systems, all-electric drive systems as well as hybrid drive systems. Among them, the all-electric drive system IM machine has the best energy-saving performance of up to 66% (Zhang 2008). However, the hybrid drive system machine could fit into a niche market at an intermediate cost. The utilization of a variable-displacement pump (VDP) and variable-speed drive (VSD) could also lower energy consumption of IM machines because of their ability to make adjustments to a machine's operation to meet dynamic load demands (Intelligent Energy-Europe 2006; Wang and Chen 2016). For the heating items of an injecting system, the better screw design (Bolur 2000; Myers et al. 2008) and insulation of the heating barrel (Taylor et al. 2007) could reduce energy consumption, which occupies 20–50% of the input energy during a machine's operation (Kent 2008a). For the clamping system, a toggle clamp design could save up to 10% more energy when compared to a direct hydraulic clamp (Bolur 2000).

The part design, such as clamping tonnage (Rosato et al. 2000) and shot capacity (Goodship 2004), is related to the selection of machine size directly. Therefore, reduction of energy consumption during the IM process would be initiated at the product design stage (Madan et al. 2013; Weissman et al. 2010). The performance of the product is related not only to the part's shape and size but also to the chosen material. When selecting a proper plastic material for lower energy

Table 1 Review of energy-saving progress or factors of the IM machine and process in recent decades

Items	Progress or improving factors
Driving system	Hydraulic/servo/all-electric/hybrid
Injecting and clamping systems	Screw design/insulating heating barrel toggle clamp design
Part design	Clamping tonnage/shot capacity
Plastic material	Melt flow index (MFI)/cooling time/viscosity
Production rate	Specific energy consumption (SEC)
Mold design	Gate/sprue/runner
Process parameters	Machine/process/quality variables

consumption, the melt flow index (MFI) (Rosato et al. 2001) of a material is an indicator on how to adjust the cooling time (Kazmer 2011) and viscosity. Some advanced materials with lower specific energy requirement, such as low back pressure (Dow 2011) and viscosity (Bayer 2007), have been developed. In order to reduce the specific energy consumption (SEC) of an IM machine or site, enlarging the machine size or the production rate would be one of the options (Kent 2008b; Gutowski et al. 2006; Qureshi et al. 2012). Mold design parameters, such as the gating system, sprue geometry, and runner layout, are important to the entire energy usage (ETSU&BPF 1999). A hot runner design could lower the overall energy consumption compared to a cold runner design (Rosato et al. 2000). Adjusting process parameters, such as machine, process, and quality variables, would reduce energy consumption to a certain level (Chen and Turng 2005). However, not so much research results regarding these relationships of the IM process were presented (Kent 2008a). Another no-cost investment strategy to improve energy efficiency is through process parameter optimization. Various types of optimization methodologies, such as Taguchi (Shen et al. 2004), genetic algorithm (GA) (Kurtaran and Erzurumlu 2006), fuzzy logic (Bharti et al. 2010), and artificial neural network (ANN) (Altan 2010), have been provided for improving the quality of a product or system, particularly in the field of the IM process.

In addition to process parameter optimization, several low-cost practices, such as checking the cooling pipework, reviewing mold performance, carrying out routine maintenance, etc., also can reduce the energy consumption of the IM process instantly within a certain amount. However, applying the energy management system (EMS) onto the IM process would bring substantial long-term improvements and provide further tools for reducing energy consumption (Hordeski 2004). The EMS could optimize the energy usage efficiency for both the individual IM machine and the entire site. The EMS has been utilized for saving energy since 1982 by managing the energy usage of sites or facilities. The developmental progress of the EMS has been published by Cheng et al. (2015). Here, a brief introduction of the historical/technological progression of EMS is described: (1) from 1980 to 1990, the computer (Rahman and Bhatnagar 1986) replaced the microprocessor (Capehart et al. 1982) to enhance the data-processing capability; (2) from 1990 to 2000, Internet communication (Pillai et al. 1995; Sjoberg et al. 2000) enabled nationwide energy management; (3) in 2008, wireless sensors (Lee 2008) were developed for EMS; (4) in 2010, the energy information system initiated the evolution of cloud EMS. The International Organization for Standardization (ISO) standard management (Fiedler and Mircea 2012), big data and data mining technology (Velazquex et al. 2013) tapped for joint management of energy and resources; and (5) in 2013, through the integration of cloud computing technology and connecting the specific controllers with the related sensors (Ma 2012), the capability of collecting and processing big data while controlling the energy-saving process was achieved. The represented function groups included graphic tool, optimization, site-specific strategies, scheduling, demand response control, thermal comfort control, modeling, occupancy detection, energy auditing, dimmer control, decision support tools, and big data analysis.

Several EMSs have been applied to IM processing management since 2008, such as Ethernet communication protocol (Lee et al. 2008) and ISO standard management principles (ARBURG 2016). However, the cloud energy management system (CEMS), still a burgeoning technology, has yet to be commonly used for reducing IM machine energy consumption. Therefore, a CEMS, developed by a local company called Chunghwa Telecom, will be installed on two IM machines to explore optimization of energy savings during the IM process in this study.

CEMS

Along with the developing tendency of EMS, a CEMS, named intelligent Energy Management Network (iEN), was launched by Chunghwa Telecom in 2011 (Cheng et al. 2015). The EMS is similar to the operating system (OS) of the traditional personal computer (PC), and the CEMS is like the cloud APP of the smartphone or the tablet PC. The advantages of CEMS include shared software resources and continuously upgraded functions. The CEMS consists of three service modes, including the software as a service (SaaS), the platform as a service (PaaS), and the infrastructure as a service (IaaS). The SaaS is a software license and delivery model, in which the software is licensed on a subscription basis and hosted centrally on the cloud. The developed optimization methodologies, as mentioned above for machine, process, and quality variables, could be installed in the SaaS as one of the licensed software. Here, two advanced functions, including an expert system for model-based control and a measurement and verification (M&V) system for measuring the saved energy, were developed in the layer of the SaaS. Based on the operational conditions, the expert system could simulate a simplified factory EMS. This model treats a factory as a grey box with energy cost, E; raw materials, R; and the created product value, V. Referring to the optional pricing model, a modified Black-Scholes equation (Black and Scholes 1973) could be used to simulate the factory energy usages by

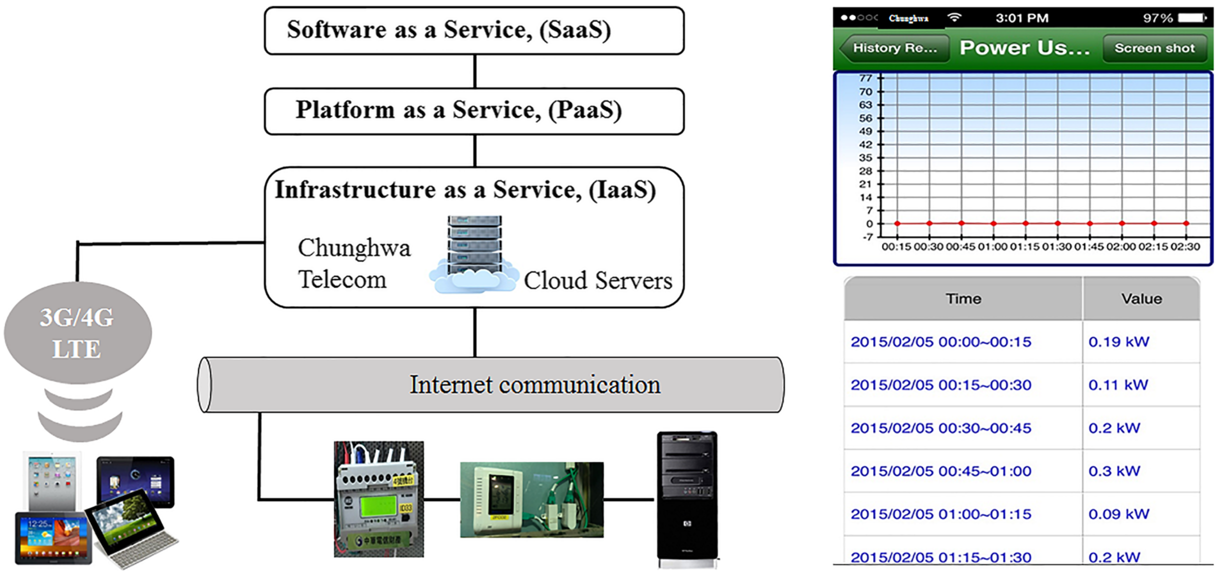
$$\frac{\partial V}{\partial t}+\gamma_E E\frac{\partial V}{\partial E}+\gamma_R R\frac{\partial V}{\partial R}+\frac{1}{2}\sigma\left(E^2\frac{\partial^2 V}{\partial E^2}+R^2\frac{\partial^2 V}{\partial R^2}\right)-\gamma_V V=0 \tag{1}$$

The PaaS denotes a computing platform and a solution stack as a service. In this model, the consumer could create an application or service by using the tools/libraries from the cloud service provider. The PaaS provides the computing resources for application design, development, test, and deployment as well as Web services. The IaaS is a provision model in which the equipment used for services is organized, such as a virtual-machine disk image library, raw block storage, and file or object storage, firewalls, load balancers, IP addresses, virtual local area networks (VLANs), software bundles, etc. In this study, the digital power meter, current transformer, IP address, and Internet communication network were utilized as contents of the IaaS. The digital meter is HC-6600, with an input voltage of 85–500 V, communication protocol RS-485. By integrating these three service models, the service structure of iEN is illustrated in Fig. 1a. Figure 1b demonstrates one of the users' mobile application platforms. These application platforms include electrical energy usage records and other environmental information. The users could obtain the timely price of electricity, energy usage, and environmental condition of sites, factories, and facilities, and adjust the operating parameters through the mobile devices or Internet for saving energy.

Experimental setup

The main benefit of the cloud EMS and continuous diagnosis of energy consumption, process dynamics, and product quality during the IM process would be the possibility of acquiring big data for future decision-making regarding investment in a new IM process, machines, or devices for energy savings. Therefore, an optimizing process example of energy savings by utilizing the cloud EMS on IM machines is presented in this study. Two 140-T horizontally oriented, servo-hydraulic IM machines (140DH, Outstanding Machinery MFG. Co. Ltd., Taiwan) were utilized for carrying out the IM process, as shown in Fig. 2a. In order to highlight the optimizing process of energy saving during the IM process, one of the IM machines was installed with the variable-frequency drive (VFD) (A510-2040, TECO Company, Taiwan), as shown in Fig. 2b. The rated output capacity and current of the VFD are 32.4 kVA and 85.0 A, respectively. The operating frequency range is from 0.1 to 400 Hz for a motor of 30 HP. Another IM machine was as purchased. Both IM machines were instated with the digital meter and connected to an iEN platform for energy usage diagnosis. The adopted plastic material was polycarbonate (PC) (LEXAN EXL1414, GE, USA) for manufacturing the back shell of a mobile phone, as shown in Fig. 2c. The sizes of the molded sample were 154.08 mm long, 76.22 mm wide, and 0.78 mm thick. The tolerance of the molded sample is 0.2 mm. The utilized material and part design could be recommended through the database of CEMS for lower energy consumption and cost.

The structure of the experimental setup is shown in Fig. 3, illustrating the communication of manufacturing information. The energy consumption of the IM machine during the manufacturing process was measured by the digital meter and transmitted to the iEN through the Internet for recording, calculation, optimization, and presentation. In the SaaS of the iEN, timely electricity price, weather report, and producing history could be utilized to make a decision for products of the lowest energy consumption. The sampling rate of the meter was 0.5 Hz. The product quality was collected by the operator and transmitted to the iEN through a mobile phone. The assessment of product quality could also be accomplished by a robot, measuring gauge, and CCD camera, and forwarded to the iEN automatically for adjustment or design of new products, processes, or machines. From information of product quality, the operator or manager could remotely control the operating conditions, producing amount, or adopted material through a mobile phone or laptop for the better producing efficiency. The operation and product information stored in the iEN could also provide instant information



(a) **(b)**

Fig. 1 **a** Structure of cloud EMS and an iEN platform which consists of three service models, i.e., SaaS, PaaS, and IaaS; **b** users' mobile application platform, indicating the electrical energy usage records and other environmental information

for customers to make an order, change the design, and manage the shipment of a product. These information and methodologies provided by the iEN could accurately evaluate the tendency and energy savings of investments in new products, the IM process, and machines.

The process optimization approach utilized in this study is one factor at a time (OFAT) of machine variables. The operating conditions include melting temperature (310.0~350.0 °C), mold temperature (110.0~130.0 °C), and clamping force (120.0~160.0 T), as listed in Table 2. The default condition was melting temperature 340.0 °C, mold temperature 120.0 °C, and clamping force 140.0 T. First, the energy savings of IM processes with/without the VFD were compared under the default condition. Then, the sequence of optimizing the operating parameters was melting temperature, molding temperature, and clamping force. The process parameters could also be optimized by various optimizing methodologies stored in the SaaS platform of the iEN. Here is one of the methods.

To compare and calculate the saved energy before and after the installation of the iEN, the international performance measurement and verification protocol

(a) 140T Injection Molding Machine **(b) Variable Frequency Drive** **(c) Molded sample**

Fig. 2 Photographs of **a** a 140-T IM machine; **b** a 32.4-kVA VFD; and **c** a molded PC sample for the back shell of a mobile phone

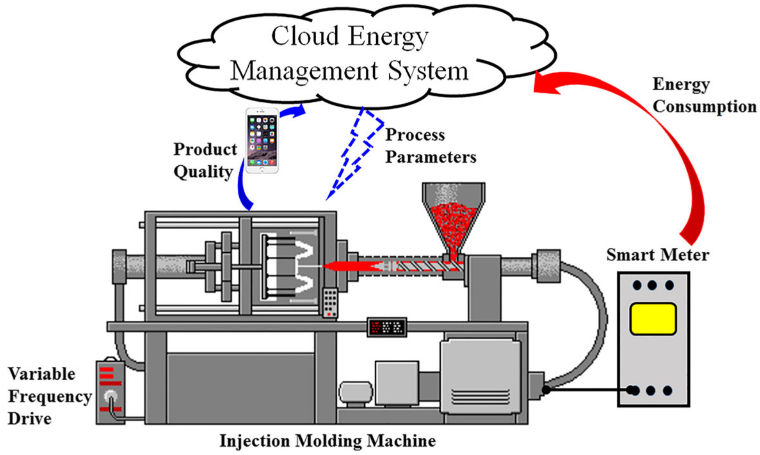


Fig. 3 The structure of the experimental setup illustrates the transfer of manufacturing information, including energy consumption, product quality, and process parameters

(IPMVP) was utilized. The IPMVP, provided by the Department of Energy, USA (2007), presented four options to measure energy savings, based on the system configuration and data availability. The saved energy before and after the implementation of the iEN was compared on a consistent basis, as shown in the following equation:

$$\begin{aligned} &\textit{saved energy} = \\ &(\textit{baseline energy consumption} - \textit{reporting energy consumption}) \\ &\pm \textit{adjustments} \end{aligned} \tag{2}$$

Adjustments are related to the physical/environmental/instrumental changes for the testing cases. For a manufacturing plant, the adjustments could be from the different consumed energy between the outmoded and newer replaced machines. The energy savings could be calculated as

$$\begin{aligned} &\textit{energy savings}\ (\%) \\ &= (\textit{normalized saved energy} \div \textit{baseline energy consumption}) \\ &\times 100\% \end{aligned} \tag{3}$$

The saved electrical energy could be transferred to a reduced carbon dioxide (CO_2) amount by

$$\begin{aligned} &\textit{reduced amount of}\ CO_2(\text{kg}) \\ &= \textit{saved electrical energy}\ (\text{kWh}) \\ &\times \textit{electricity emission factors of}\ CO_2(\text{kg}\ CO_2\text{e/kWh}) \end{aligned} \tag{4}$$

where the electricity emission factor for CO_2 is 0.521 kg CO_2e/kWh, based on the information from the Bureau of Energy, Ministry of Economic Affairs, Taiwan, in 2015.

Results and discussions

Energy savings by installing the VFD

The VFD could control an AC motor's speed and torque by varying the motor input frequency and voltage based on the applied load for the purpose of reducing electricity consumption. The installation of a VFD is suitable for conventional hydraulic-driven and servo-driven IM machines for saving energy. The energy savings of an IM machine with/without the VFD were compared. The electrical usage of these two different IM machine configurations was recorded by the iEN under operating conditions at a melting temperature of 340.0 °C, a mold temperature of 120.0 °C, and a clamping force of 140.0 T. The recorded electrical usages of the IM machines with and without the VFD (indicated by symbols of ○ and □, respectively) with respect to processing time during the fabrication process of one sample are presented in Fig. 4. In Fig. 4, during a processing time of 2 to 8 s, the electrical usage of the IM machine without the VFD showed a sharp increase of 26.4 kW at 6 s; then, it was reduced to 8.7 kW. This period was related to the mold closing and the melted plastic being injected into the mold cavity. Between 10 and 16 s of the processing time, the electrical power was kept at a stable state of 16.0~18.0 kW. This period was related to the holding and cooling stages. Between 18 and 20 s, the electrical power sharply increased to 15.1 kW at 20 s, then decreased to 6.2 kW. This period was related to the mold opening and the part ejection stage. Through the VFD, the electrical usage variations of the IM machine were reduced. The average values of the electrical usage of the IM machine with and without the VFD were 9.1 and

Table 2 Operating conditions of the IM process

Melting temperature (°C)	Mold temperature (°C)	Clamping force (T)
310.0	110.0	120.0
320.0	115.0	130.0
330.0	120.0	140.0
340.0	125.0	150.0
350.0	130.0	160.0

14.5 kW, respectively. After a 1-h test, the consumed electrical energies of the IM machine with and without the VFD were 12.4 and 21.1 kWh, respectively. The overall energy savings of the IM machine with the VFD were 41.3%. These energy-saving benefits of installing the VFD would be presented on the SaaS platform of the iEN by comparing the energy usages of these two IM machines. This new information and its methodologies could be applied to other devices and useful for designing new IM machines.

Optimizing the melting temperature through the iEN

It is our interest to further optimize the process parameters by adopting the OFAT approach and evaluate the related energy savings after installing the VFD. Again, the optimizing approach of process parameters and profitable methodologies could be provided by the iEN. First, the various melting temperatures of 310.0, 320.0, 330.0, 340.0, and 350.0 °C were compared. To compare the energy savings under various melting temperatures, these two IM machines were operated under the settings at a mold temperature of 120.0 °C and a clamping force of 140.0 T. The recorded electrical usages and product qualities of the IM machine with and without the VFD (indicated by symbols of ○ and □, respectively) with respect to melting temperature are presented in Fig. 5. The electrical usages and product qualities were indicated by empty and filled symbols, respectively. The utilizing principles of symbols will be presented in the following sections. In Fig. 5, the electrical usages of the IM machine with and without the VFD demonstrated a concave shape and had minimum values of 2.4 and 3.1 kWh at a melting temperature of 320.0 °C, respectively. Then, they increased with the melting temperature and had maximum values of 2.7 and 3.9 kWh at a melting temperature of 350.0 °C, respectively. The product quality of 100% happened at melting temperatures of 320.0, 330.0, and 340.0 °C and 330.0, 340.0, and 350.0 °C for the IM machine with and without the VFD, respectively.

The energy savings of the IM machine with the VFD with respect to the various melting temperatures are illustrated in Table 3. Under the conditions of 100% product quality, the maximum energy savings were 33.8% at a melting temperature of 330.0 °C. Therefore, the optimized melting temperature was 330.0 °C, and this will be fixed in the following procedures.

Optimizing the mold temperature through the iEN

In addition to melting temperature, mold temperature also affects the energy usage and product quality of the IM process. It is our interest to further optimize the mold temperature. To compare the energy savings under various mold temperatures of 110.0, 115.0, 120.0, 125.0, and 130.0 °C, these two IM machines were operated under the settings at a melting temperature of 330.0 °C and a clamping force of 140.0 T. The recorded electrical usages and product qualities with respect to mold temperature are presented in Fig. 6. In Fig. 6, the electrical usage of the IM machine with and without the VFD demonstrated a concave shape and had minimum values of 2.6 and 3.6 kWh at a mold temperature of 120.0 °C, respectively. For the IM machine with and without the VFD, the maximum values of 3.4 and 4.3 kWh appeared at a mold temperature of 110.0 °C, respectively. The

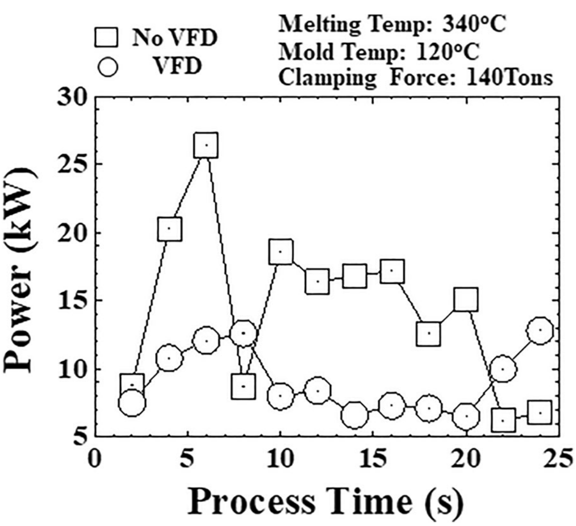


Fig. 4 The recorded electrical powers of the IM machine with and without the VFD (indicated by circles and squares, respectively) with respect to process time during the fabricating process of one sample

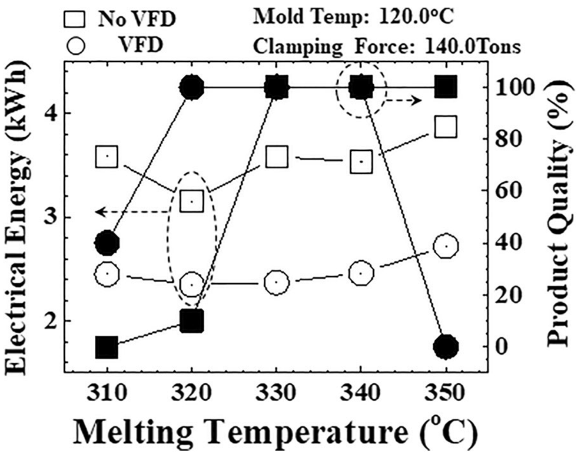


Fig. 5 The consumed electrical energy of the IM machine with and without the VFD (indicated by empty circles and squares, respectively) and product quality (indicated by filled symbols) under various melting temperatures

100% product quality happened at mold temperatures of 120.0 and 125.0 °C and 110.0, 115.0, and 120.0 °C for the IM machine with and without the VFD, respectively.

The electrical energy savings of the IM machine with the VFD with respect to various mold temperatures are illustrated in Table 4. Under the conditions of 100% product quality, the maximum energy savings were 28.0% at a mold temperature of 120.0 °C. Therefore, the optimized mold temperature was 120.0 °C, and the following experiments will fix the melting temperature at 330.0 °C and the mold temperature at 120.0 °C.

Optimizing the clamping force through the iEN

Clamping force is applied on the IM machine through the hydraulic or electrical force to keep the mold closed against a force from the injected plastic material. And it should be not less than the injection force to avoid flash. It is our interest to evaluate how the clamping force affects the energy usage and the product quality of the IM process. To compare the energy savings under various clamping forces of 120.0, 130.0, 140.0, 150.0, and 160.0 T, these two IM machines were under the operating settings at a melting temperature of 330.0 °C and a mold temperature of 120.0 °C. The electrical usage and product quality with respect to the clamping force are presented in Fig. 7. In Fig. 7, the electrical usages of the IM machine with the VFD demonstrated a convex shape and had a maximum value of 3.7 kWh at a clamping force of 150.0 T. However, the electrical usages of the IM machine without the VFD increased monotonically from 3.5 to 3.7 kW. The 100% product quality happened at a clamping force of 140.0 T for the IM machines with and without the VFD.

The electrical energy savings of the IM machine with the VFD with respect to the various clamping forces are illustrated in Table 5. Under the conditions of 100% product quality of the IM machine with the VFD, the energy savings were 1.2% at a clamping force of 140.0 T. The results indicated that the adjustment of a clamping force may not cause significant energy savings for the IM machine. Therefore, through the OFAT approach provided by the iEN, the optimized operating conditions of the IM machine were at a melting temperature of 330.0 °C, a mold temperature of 120.0 °C, and a clamping force of 140.0 T.

Table 3 Energy savings of the IM machine with the VFD under various melting temperature settings

Melting temperature (°C)	Energy savings (%)	Product quality (%, with VFD)
310	31.68	40
320	25.49	100
330	33.82	100
340	30.43	100
350	29.61	0

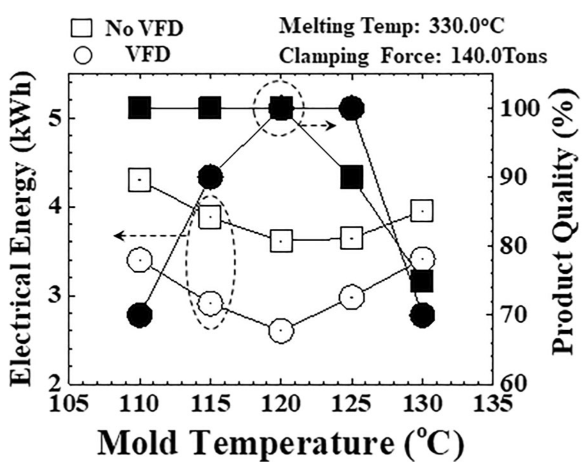


Fig. 6 The consumed electrical energies of IM machines and product qualities under various mold temperatures

Table 4 Energy savings of the IM machine with the VFD under various mold temperature settings

Mold temperature (°C)	Energy savings (%)	Product quality (%, with VFD)
110	21.0	70
115	25.0	90
120	28.0	100
125	18.22	100
130	13.67	70

Energy savings and CO_2 reduction calculated by the iEN

Through the connection of PaaS, the process dynamics, product quality, and energy usage could be transmitted and recorded on the cloud database of the iEN for further analysis of the energy savings. Here, two same models and operating periods of IM machines were utilized. The same mold, material, and operating conditions were applied on the IM process. Therefore, the adjustments in Eq. (2) could be neglected. The as-purchased IM machine could be adopted for providing the baseline energy consumption, and the one with the VFD could demonstrate the reported energy conservation. Through the 4-h optimizing procedure of operating conditions, the baseline and reported energy consumptions were 91.4 and 42.5 kWh, respectively, as presented in Table 6. After the optimizing procedure, the total electricity savings of the IM machine with the VFD were 53.5%, which included the additional electricity savings (12.2%) caused by process parameter optimization. Through installing the VFD and the iEN on the IM machine, the electricity cost could save NT$ 26,363 per month. And the payback period of the installation fee of the VFD and the iEN could be within 4 months, under our experimental conditions. By shifting the manufacturing period to lower electricity time and adopting material of lower price and SEC, the electricity and manufacturing costs would be saved further. The saved electricity and reduced carbon dioxide (CO_2) amounts were 107,200.5 kWh/year and 55,851.5 kg/year, respectively. If this system was applied on the IM machines manufactured by China in 2014, assuming that all the IM machines were servo-hydraulic type, the total saved electricity and reduced carbon dioxide (CO_2) amount would be 8962.7 GWh/year and 4.7 Mt/year, respectively. These results would benefit the mass promotion of the iEN to the IM industries for saving energy and conserving the environment. Continuous analysis of the optimization process, energy savings, resource conservation, and waste reduction of the IM process using the iEN has shown overall benefits to the IM process, the machines, and the future decisions and designs regarding new products.

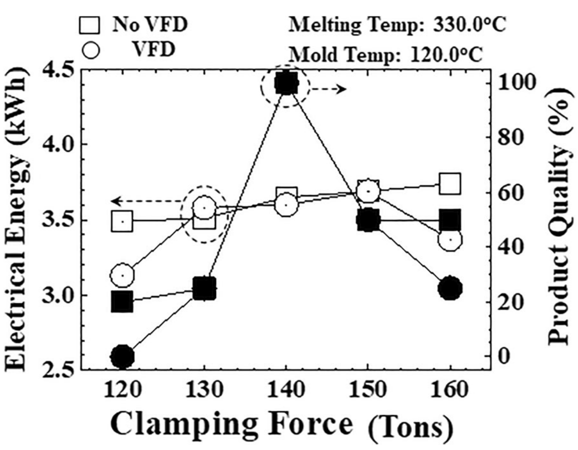


Fig. 7 The consumed electrical energies of IM machines and product qualities under various clamping forces

Conclusions

The injection molding (IM) process is a widely used manufacturing process for injecting material into a mold for producing a diverse array of parts. It includes several energy-consuming procedures, such as heating plastic pellets, forcing melted polymer into a mold cavity, and cooling down the molded products. In this study, developmental factors of IM machines and processes along with energy savings progress are reviewed. In addition to several machining factors and process parameter optimizations, applying an energy management system

Table 5 Energy savings of the IM machine with the VFD under various clamping force settings

Clamping force (T)	Energy savings (%)	Product quality (%, with VFD)
120.0	10.2	0
130.0	5.0	25
140.0	1.2	100
150.0	0.0	50
160.0	10.9	25

Table 6 Energy consumptions and savings of IM machines after installing the VFD and iEN

Item	Unit	Amount
Baseline energy consumption	kWh	91.43
Reported energy consumption	kWh	42.48
Energy savings	%	53.5
Energy cost saving	NT$/month	26,363
Payback period	Month	4
Saved energy	kWh/year	107,200.5
Reduced CO_2	kg/year	55,851.46

(EMS), as well as new tools to reduce energy consumption to the IM process, has the potential for great improvements in the long term. A cloud energy management system (CEMS), called the intelligent Energy Management Network (iEN), which was launched by Chunghwa Telecom, was installed on two IM machines to illustrate the optimization of energy savings by a variable-frequency drive (VFD) and process parameter optimization. Through the recorded process dynamics, the energy usage, and product quality of the IM process using the iEN, the energy savings could be analyzed by the expert, measurement and verification (M&V) systems on software as a service (SaaS) platform. The electricity savings on the IM machine after installing a VFD were 41.3%. Further optimization by using the one-factor-at-a-time (OFAT) approach to measure the process parameters, such as melting temperature (310.0~350.0 °C), mold temperature (110.0~130.0 °C), and clamping force (120.0~160.0 T), was carried out. The experimental and analyzed results indicated that the optimal operating conditions were at a melting temperature of 330.0 °C, a mold temperature of 120.0 °C, and a clamping force of 140.0 T. Through the optimization procedure of the process parameters carried out by the iEN, further electricity savings of 12.2% were added. Therefore, the saved electricity cost and payback period of installing the VFD and the iEN were NT$ 26,363/month within 4 months, respectively. The saved electricity and reduced carbon dioxide (CO_2) amounts were 107,200.5 kWh/year and 55,851.5 kg/year, respectively. Continuous analysis of the optimization process, energy savings, resource conservation, and waste reduction of the IM process using the iEN has shown overall benefits to the IM process, the machines, and the future decisions and designs regarding new products.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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