INNOVATIVE INDUCTION-HEATED HIGH-TEMPERATURE STEAMER USING VOLTAGE-FED HIGH-FREQUENCY RESONANT INVERTER

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ABSTRACT-This paper presents an innovative prototype of a new conceptual electromagnetic induction-based fluid heating appliance using voltage-fed series capacitor-compensated load resonant high-frequency IGBT inverter with a phase-shifted PWM and a power factor correction schemes. Its operating characteristics in steady-state and dynamic state are illustrated including unique features and evaluated on the basis of its computer simulation and experimental results of 10kw breadboard appliance developed for hot water producer and superheated steamer.

1.INTRODUCTION

In recent years, the electromagnetic induction-based heating energy processing systems which are controlled by the voltage-fed or current-fed high-frequency resonant inverters using the latest IGBTs have attracted special interest from the advantageous viewpoints of high-efficiency, high-reliability, safety, cleanness, compactness, light weight, rapid responses, as well as stable temperature tracking and precise temperature control ability.

With tremendous advances in the latest power semiconductor devices such as IGBTs, MOSFETs, MCTs, SITs, high performance resonant inverters for induction-heating power supplies have been widely applied for the forging, forming, annealing, surface hardening, soldering, brazing, scaling, welding and melting processes of various metals. The new products of induction-heated appliances using a single ended high-frequency load resonant inverters operating at ZVS mode, by which cooking pan, rice cooker/warmer, fryer, steamer, hot water producer, dryer and exhausted gas cleaner are able to be developed for consumer power electronic appliances.

Under these technological backgrounds, the authors have proposed a novel electromagnetic induction-based flow-through metal package fluid-heating appliances which make use of some voltage-fed PWM high-frequency load-resonant inverters using IGBTs.

This paper presents an innovative product of the electromagnetic induction-based fluid heating appliance with high-frequency resonant inverter composed of a phase-shifted PWM series loaded-resonant inverter using the third generation IGBT modules and their driver interface IC, the advanced auto-tuning PID gain controller, and specially designed thin metallic laminated assembly induction heater incorporated into the non-metal vessel or tank in the pipeline plants.

Its inherent steady-state operating characteristics are illustrated as an efficient induction-heated Dual Packs Heater(DPH), exchanger and are also evaluated as induction-heated boiler, steamer, evaporator and dryer from a practical point of view.

2.ELECTROMAGNETIC INDUCTION-BASED FLUID HEATING APPLIANCE

Fig.1 shows a schematic system configuration of the new conceptual electromagnetic induction-based fluid (liquids or gases, powder, particles)-heating appliance using a voltage-fed series resonant PWM high-frequency inverter with an active power-filtering scheme.

This unique fluid-heating appliance used for the industrial, chemical, and consumer pipeline network systems is basically composed of a single-phase diode rectifier with no smoothing DC capacitor filter link or active three-phase PFC converter, a voltage-fed full-bridge type series load resonant IGBT inverter with a constant frequency phase-shifted PWM power regulation scheme, a specially-designed dual packs heater(D.P.H.) made of electromagnetic induction heated type fluid-through thin metallic layer assembly with many spots and mechanically wave-like processed flow channel slits in order to generate natural turbulence in the vessel.

For efficient direct fluid heating, this hot water producer and super heated steamer using induction-heated DPH is designed so as to operate a unity power factor correction and active harmonic current compensation.

This induction heated dual package(D.P.H.) on the basis of the induced eddy current-based thin metal heating principle with a large amount of heating surface is tightly and incorporated into the nonmetallic vessel or tank the working coil to generate the high-frequency flux due to

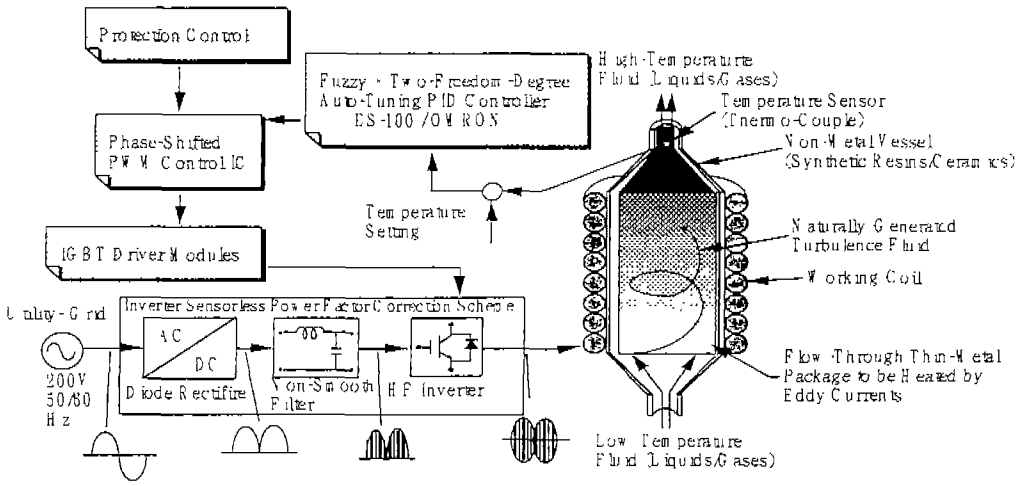


Fig. 1 New schematic-heated electrical energy conversion & utilization

high-frequency inverters.

The fluid flowing through induction-heated dual packs heater can be directly heated on the basis of heat exchange principle.

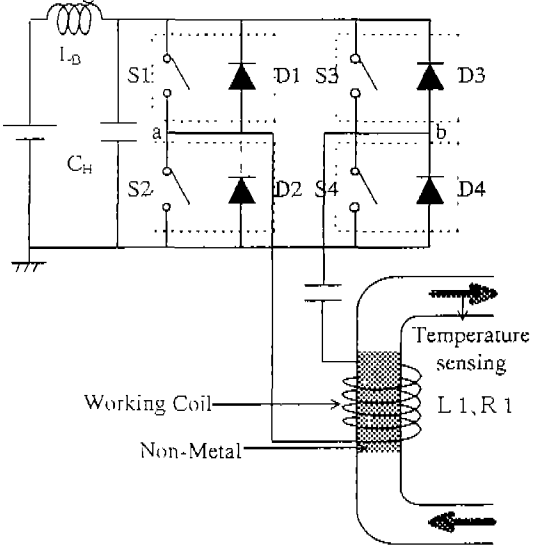
A precise and stable temperature control feedback loop with an intelligent auto-tuning PID controller and a thermocouple temperature sensor is implemented for inverter type induction-heated boiler with DPH .The diagnostic management can be easily achieved on the basis of observing the temperature difference.

This moving fluid-heating appliance using high-frequency inverter is more suitable for fluid heat transfer processing plants as compact and efficient heat exchanger based upon induction-heated boiler, because of cleanness, compactness, high efficiency, quick temperature tracking response, precise temperature control, excellent controllability, high-reliability and safety.

It is noted that this fluid heating appliance is more cost-effective as an electromagnetic induction- heated boiler. hot water supplier and superheated steamer required for a variety of pipeline heat energy processing systems in addition to hot gas-related dryer. It is experimentally proved that this innovative induction-based fluid-heating appliance using voltage-fed high-frequency inverter is cost-effective for liquid and gas heating appliances from a practical point of view.

3.SERIES LOAD RESONANT PWM INVERTER

Fig.2 shows the voltage-fed full-bridge type series loaded-resonant PWM inverter using the latest IGBT modules with intelligent driver IC. In general, the power matching transformer may be inserted between the inverter output terminals and working coil for induction heated dual packs heater(D.P.H.) incorporated into the vessel in order to match the load impedance. The operating voltage and current waveforms of the series- loaded resonant inverter operating at a phase-shifted PWM mode are illustrated in Fig.3. The output voltage and power of this full-bridge resonant inverter using IGBTs can be continuously regulated by the constant frequency phase-shifted PWM scheme. As can be observed in Fig.3, each turn-on switching currents of the active power switches S1/S2 in the left bridge leg becomes both positive value in PWM regulation mode.



C_H:High-frequency pass capacitor

L_H:High-frequency block inductor

Fig2. A voltage-fed full-bridge type series loaded resonant inverter

As a result, the active power switches S1/S2 are to operate at hard-switching in the turn-on mode. However, the active power switches S1/S2 can achieve a soft-switching in the turn-off operation mode under a condition of both zero current and zero voltage transition in spite of the phase-shifted PWM control process and wide load parameter variations. The active power switches S1/S2 can achieve the zero current soft-switching by means of lossless inductive snubbers

On the other hand, the active power switches S3/S4 in the right bridge leg can turn-on under a condition of the zero current and zero voltage soft switching in spite of phase-shifted PWM processing and load parameter variations.

In case of fo>fr (fo : Inverter frequency, fr : Series resonant frequency), the active switches S3/S4 must always turn off at a certain hard switching condition and turn on at soft-switching condition. Therefore, the active switches S1/S4 can achieve the zero voltage soft-switching by means of lossless capacitor snubbers.

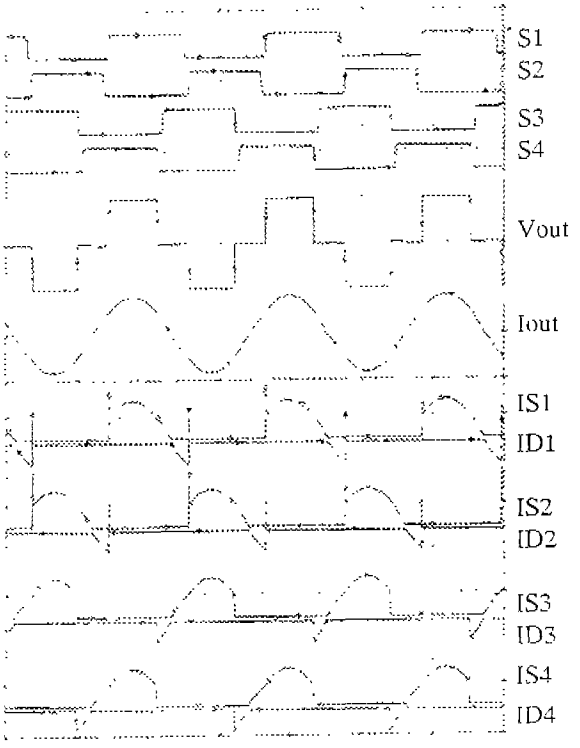


Fig. 3 Voltage and current waveforms

4. INDUCTION-HEATED FLOW-THROUGH METALLIC PACKAGE ASSEMBLY

Fig.4 indicates a specially-designed eddy current-heated metallic package developed by the authors, which can flow through the moving fluid such as liquids, gasses, powder and particles.

The induction-heated wave-like thin stainless-steel layer package with flow-through many spots and fluid-flow channels in the non metal cylindrical vessel is demonstrated in Fig.5. Detail internal structure of this metallic thin layer (stainless steel plate) package assembly to be heated directly by the eddy current-based losses is displayed in Fig.6. In addition, the fluid turbulence when the fluid flows through the dual package assembly can be naturally generated by using induction-heated dual package assembly. When the fluid (liquids, gases, powder) flows through the unique metallic package inserted into the ceramic vessel or tank with a work coil, which is located to the pipeline system.

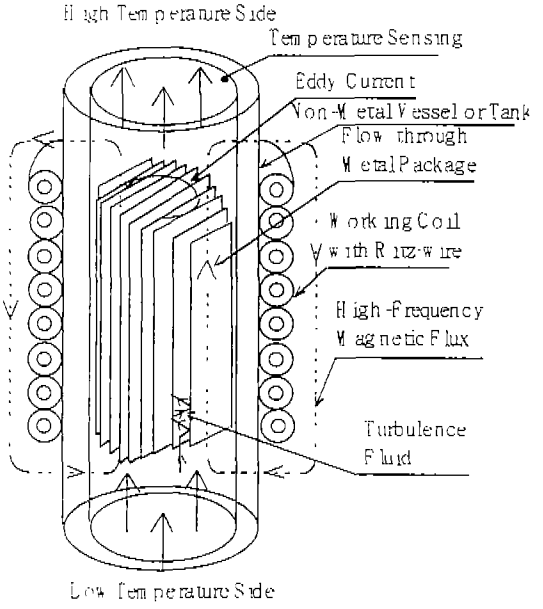


Fig. 4 Heating Package in the vessel and tank

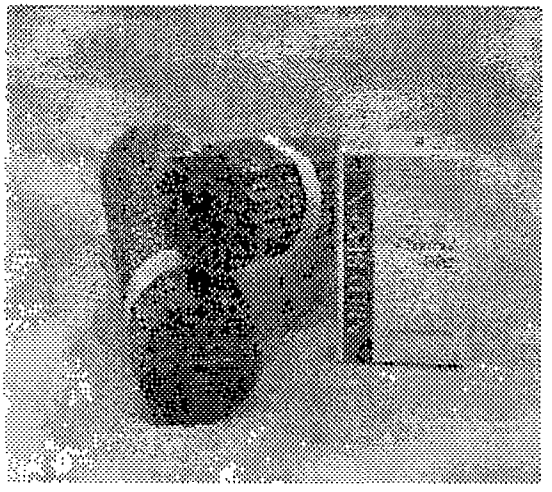


Fig. 5 Induction-heated metallic package

This turbulence moving fluid is to be heated instantaneously and uniformly on basis of the induced eddy current based-heat energy with in the large heating surface which is generated in both surfaces of thin stainless-steel package inserted into the vessel. Induction-heated dual packed heater energy can efficiently transferred and exchanged as the flowing fluid heat energy.

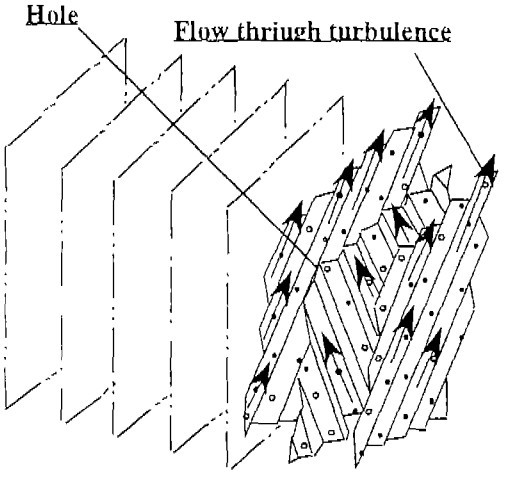


Fig.6 Internal structure of fluid-through specially-designed metal layer packing to generate turbulence

5. SALIENT FEATURES OF INDUCTION-HEATED BOILER USING INVERTER

The remarkable features of the new conceptual electromagnetic induction fluid-heated boiler using the induction-heated appliances are as follows:

(I) Eddy currents-heated conductive thin metallic package incorporated into the ceramic vessel with a working coil connected to the high-frequency resonant inverter, works as a heat exchanger. In principle, an electrical wiring for energy transmission is not needed for contactless heating.

Thus, the electrical insulation is performed. Because of maintenance free, the system reliability becomes higher as compared with a conventional resistance heater as sheathed heater.

(II) 50 μm-stainless steel package assembly as the induction-heated body is used, the heat capacity of this heating body is extremely small in addition to huge heating surfaces due to the eddy-current-based heater. The temperature rising time in fluid heating response of the vessel outlet is able to be much quicker. Rapid electrical heating is exactly realizable as hot water producer, super heated steamer, spot hot air producer and hot-gas dryer.

(III) Induction heated-fluid (liquids/gases) contact is to be exchanged by flowing through internal package assembly incorporated into the ceramic vessel in the pipeline. Heating surface due to eddy current is extremely large. In this prototype, induction heating surface of the flow-through cylindrical dual package is designed for 8.5m^2 under the small physical volumetric size of 10cm in diameter and 19cm in height.

(IV) Owing to the naturally-generated turbulence, fluid is uniformly heating by the induction heated DPH which is based on the inherent fluid flow-through metallic thin dual package structure with numerous spotted holes and complicated and split flow channels. The temperature distribution of the moving fluid obtained from the outlet of the vessel/tank with the work coil can be precisely kept constant, in which the flow-through heating package is tightly inserted into the vessel. Temperature distribution of induction heating dual package has a constant temperature gradient. Ease to detect the uniform temperature output of the moving turbulence fluid in the pipeline can be confirmed.

(V) Ease to control under stable and precise conditions by means of a fixed frequency phase-shifted PWM regulation under a wide temperature setting condition because of an auto-tuning PID-based feedback scheme. Microprocessor-based control implementation can be easily introduced.

(VI) Temperature regulation range of fluid heating within the vessel in the pipeline is extremely wide from a low temperature to a high temperature more than 800°C with a precise temperature setting. The super heated steamer more than 200°C can be realized by the induction heated DPH boiler.

(VII) Energy conversion efficiency of this new conceptual appliance is high. Because of energy saving , the running cost becomes relatively cheap.

(VIII) Compactness in volumetric size. In practice, lighter weight is to be achieved

6. EXPERIMENTAL SET-UP AND NEW APPLICATIONS

Table I indicates the practical design specifications of the feasible electromagnetic induction-based fluid- heating appliance using a series loaded-resonant IGBT inverter with a self-tuning PID-based feedback control scheme and active filter for current harmonic compensation and power factor correction schemes.

Fig.7 illustrates the steady-state operating characteristics in case of this electromagnetic induction-heated boiler. Observing operating characteristics in Fig.7, the AC output power of the high-frequency inverter can be continuously regulated according to the adjustment of the phase-shifted angle ϕ ($0^\circ \leqq \phi \leqq 180^\circ$)as a control variable. Power conversion efficiency η is estimated by equation (1)

Table 1 Design specifications of inverter-fed type induction-heated boiler

Items	Design Specification
Input Voltage	Single-Phase 200Vrms
Regulated Output power	0～10kw
Power Regulation Strategy	Constant-Frequency Phase-Shifted PWM
Operating Frequency	30kHz
Size of DPH	ϕ t00mm × h190mm
Temperature Control System	Fuzzy+Two Freedom Auto-tuningPID

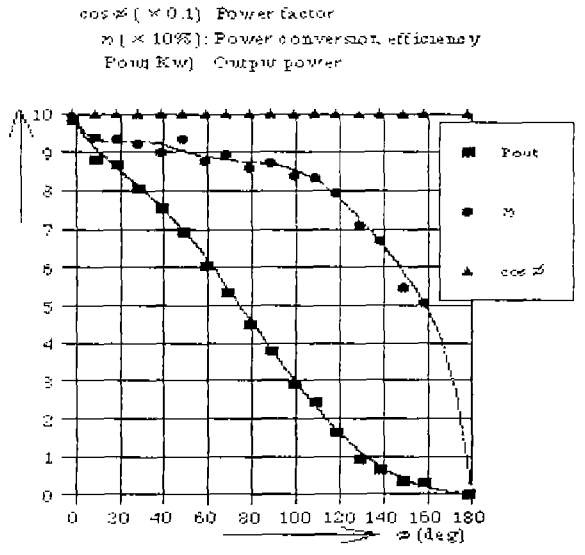


Fig. 7 illustrates the steady-states total operating characteristics in case of this electromagnetic

$$\eta = \frac{P_{OUT}}{P_{IN}} \times 100[\%] \qquad (1)$$

$$P_{OUT} = c\Delta T \frac{\Delta Q}{860} \times 1000[W] \qquad (2)$$

where, Pin:input power

Pout:output power estimated by equation(2)

ΔT=T2-T1

T2=temperature in the inlet of the vessel

T1=temperature in the outlet of the vessel

c≒1.0 (specific heat)

The input voltage and current waveforms in utility power source which is observed by this feasible induction heated DPH boiler appliance are displayed in Fig.8.

The output high-frequency current waveform with 60Hz AC voltage envelope corresponding to the input voltage and current waveforms100 is illustrated in Fig.9. The unity power factor correction and sinewave line current shaping compensation in utility AC grid bus are sufficiently achieved without an active filtering control implementation with a high precision current sensor.

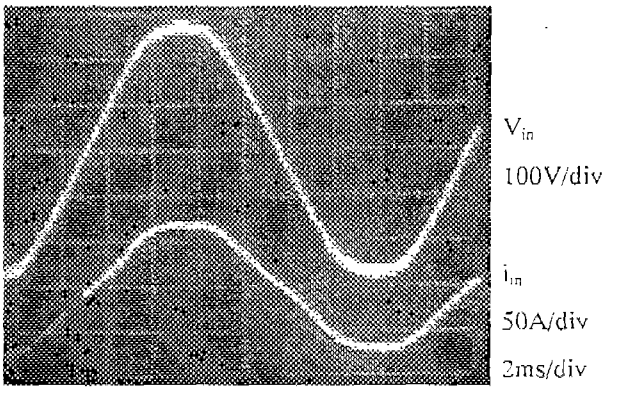


Fig.8 Input voltage and current waveforms

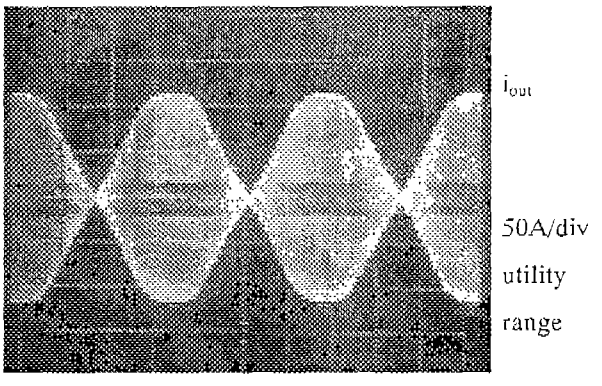


Fig9.Output current waveform

Fig.10 shows the innovative induction heated DPH boiler system using the high-frequency inverter which can generate the low pressure super heated vapor from 200℃ to 1000℃. This super heated steamer is composed of two induction heated DPH boilers to produce saturated steam and super heated high-temperature vapor.

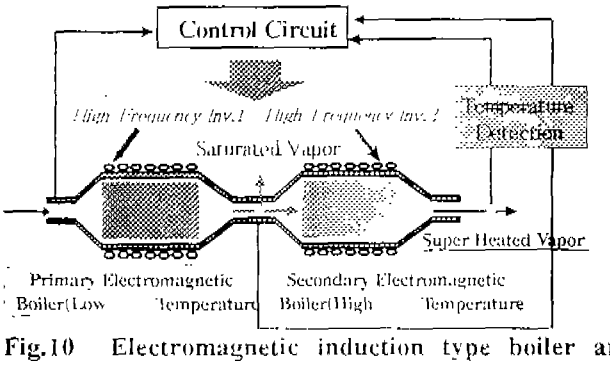


Fig.10 Electromagnetic induction type boiler and evaporator hybrid steamer.

Fig.11 indicates the temperature tracking performance of electromagnetic induction-heated DPH in case of water as moving fluid. In this figure, the measured temperature

track the preset temperature quickly. This is because this electromagnetic induction-heated DPH system uses fuzzy reasoning type feed forward and feed back PID auto-tuning controller.

Fig.12 shows temperature rising response of electromagnetic induction-heated DPH system used water. In this figure, temperature of moving fluid rise up to 200°C for only about one minute. Owning to these temperature characteristics, it is mentioned that electromagnetic induction-heated DPH boiler has more excellent higher performance than conventional boiler.

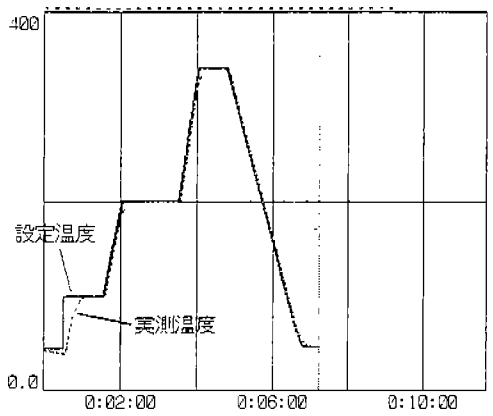


Fig.11 Temperature Tracking

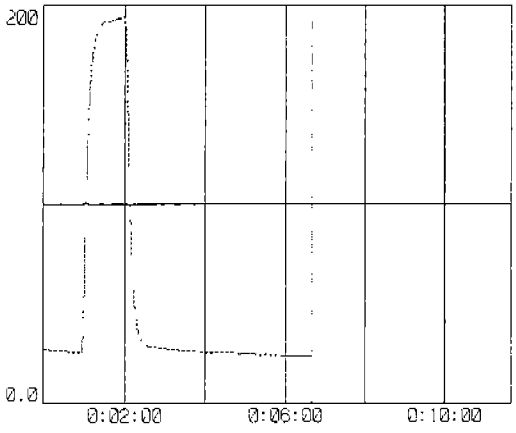


Fig.12 Temperature Rising Response

7.CONCLUSIONS

In this paper, an innovative prototype of the electromagnetic induction-based fluid-heating appliance using the high-frequency resonant inverter which is named induction-heated DPH boiler has been successfully proposed on the basis of a series loaded-resonant PWM high-frequency inverter operating at soft-switched PWM scheme, and its self-tuning PID temperature control scheme.

It was emphasized that epoch-making and new conceptual fluid-heating principle of this new power electronic appliance using the inverter with a phas shifted PWM scheme is based upon the electromagnetic-induced eddy current which are generated in a flow-through thin metallic package incorporated into the nonmetallic vessel or tank in the pipeline systems.

This efficient appliance driven by the voltage-fed type series-loaded resonant soft-switching PWM inverter topology using lossless snubber inductors and capacitor bridge legs has been newly introduced for a new fluid heating method based on induction heating principle.

Furthermore, it has been proved as various chemical industry plants that the new and efficient fluid heating appliances could be more cost-effective for the electromagnetic induction-heated boiler than the conventional sheathed heated type boiler which induction-heated steamer, dryer as well as induction-heated hot water producer, because of compactness in volumetric physical size, cleanness, high-efficiency conversion, quick temperature response, stable and precise temperature control realization.

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