行政院國家科學委員會專題研究計畫 成果報告

整合太陽能暨瓦斯雙效輔助技術用於提升熱泵熱水器性能之研究(III)

研究成果報告(精簡版)

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中文摘要

太陽能熱泵熱水器也可以利用熱泵循環將即熱式瓦斯熱水器的廢熱回收，用來預熱冷水，將更多比例的瓦斯燃燒熱用在熱水供應上，減少瓦斯用量，提高了整體的能源效率。若成功整合，可以在低溫、低日照場合，以複合式熱源提供熱水，且具有最大能源效率。再生熱水的水溫雖低，但蘊藏的熱量卻不少，若與初生熱水的熱量相比較，比例約為1:10。根據多次的實驗結果，節省約10%的瓦斯。本計畫是關於太陽能和瓦斯熱泵熱水器的整合，在蒸發器的型式做了調整之後，即使瓦斯熱水器連續燃燒13分鐘，熱泵循環也依然維持穩定，表示此新系統穩定，操作可靠。

關鍵詞： 熱泵、太陽能、瓦斯熱水器、廢熱回收

Abstract

Solar-assisted heat pump water heater also can be utilized to recover the waste heat from an instantaneous gas water heater, and to preheat cold water. Because of the combustion heat used on water heating being almost complete, the consumption of gas fuel decreases and whole energy efficiency increases. It the both water heaters integrate into a new one, it could supply hot water in hybrid heat sources with most energy efficiency at those places with low temperature or low solar incident. In spite low temperature the preheat water owns a bit of heat, about one-tenth of the hot water has supplied by the instantaneous gas water heater. According to lots of experiments the percentages of gas fuel saving were about from ten to twenty. This plan concerned the integration of the two different type water heaters. Once the evaporator had been modified, the heat pump subsystem could be maintained in stable while the gas fuel was burning at least thirteen minutes. This result implied the new type water heater is stable and trustable.

Keywords: heat pump, gas water heater, energy recover.

1. 介紹

多年以前，考慮到太陽能熱水器的三大背景，第一，在台灣的實際使用情形和設計理念有所衝突；第二，化石能源日益緊縮的局面越來越強烈，這一點在今年已是全球共同的感受；第三，太陽能的應用技術需要創新，是以提出本研究計畫。

依據實際經驗，國人普遍希望24小時內隨時都可供應熱水，因此要求在太陽下山以後，太陽能熱水器由電熱單元繼續產生熱水，但在夜間卻未能用完熱水，以致第二天吸收太陽能的效率變差。

原本在使用太陽能熱水系統時，當天由太陽能加熱的熱水應於當夜用盡，這是最理想的操作方式，夜晚不必加熱，第二天所需的熱水在第二天的白天再由太陽能加熱。如果第二天日出時，保溫水槽內殘留的水溫仍高，則太陽能熱水器吸收太陽能的效率變差。

照理說，電能加熱只是為了陰雨天氣所設的備用單元，平常不該啟動。但為了迎合使用者，現行採用的方法往往使太陽能熱水器轉變成大型的電熱水器，結果更耗能。實際估算下來，熱水幾乎是由電能於夜間所供應，失去了使用太陽能的本意。也就是說，國人對熱水的需求及使用習慣，一直以來都和太陽能熱水系統的發展有所矛盾，至今仍困擾著廠商。當

政府和民間致力於推廣太陽能熱水器時，必須找到更好的應用技術，來解決或降低這個衝突。改用瓦斯熱水器來代替太陽能熱水器的電熱輔助加熱，本是一條可行之路。可惜

在進一步了解之後，得知美國能源局曾對瓦斯熱水器的Energy Factor（EF）進行過調查，約在0.5到0.6之間，有些甚至只有0.4而已，能源效率竟然只有一半左右，可見得瓦斯熱水器的能源效率實在還有大幅改善空間，但卻一直被人忽略。儘管電能熱水器的能源效率大約為0.8，但因為連帶考慮發電廠的能源效率，所以電能熱水器還是比瓦斯熱水器消耗更多的能源。因此，苟能將瓦斯燃燒廢熱回收再利用，著重整體的能源效率，就可以減少瓦斯的消耗用量，降低進口能源的負擔，也對太陽能的發展有所助益，又迎合了使用者的習慣，對國家是有利益的。台灣，一個依賴進口能源的國家，若能夠提高瓦斯的利用效率，又善用太陽能，自可創造商業應用，所以，發展本計畫提議的複合式熱水器，可謂一舉數得。

經由實驗後確認，用一只額定制冷量為500瓦的熱泵系統，可將即熱式瓦斯熱水器所排放的廢熱回收，並用來預熱冷水。最終排放到環境的廢氣經過溫度測量後，已降到攝氏50度。熱泵的平衡狀態可以承受瓦斯熱水器連續15分鐘的點火操作，尚不致有危險，已可供一般家庭使用。熱泵循環從空氣熱源轉換到瓦斯廢熱熱源時，不同模式操作因熱通量的巨額改變導致的壓縮機過載，也因使用滿溢式蒸發器而改善了。整體而言，改良後的新系統達成了當初的預期目標。至於冷媒的節流膨脹閥，以目前使用的定壓膨脹閥而言，雖可安全操作，但仍以加裝電子調整的自動控制器為好，方能有效提高COP，避免效能不彰。如果能配合採用變頻壓縮機，應該可以更平順且節能的操作。

2. 研究目的

傳統的太陽能熱水器的學術研究，多半是去改良平板式、真空管式、聚焦式的太陽能集熱器，偶爾可見太陽能的光電整合研究，以熱泵為主的廢熱再生系統則非常少見，至於結合瓦斯、太陽能、熱泵系統的研究更幾乎沒有研究報告。參考本人有過的太陽能應用技術的創新經驗，例如「太陽能熱泵熱水器」—結合熱泵和太陽能的熱水系統，效能比傳統自然循環式太陽能熱水器和電熱水器都經濟，不僅吸收太陽能的效率高，而且可在陰雨天繼續供應熱水，列入台灣大學機械系　黃秉鈞教授主持的經濟部太陽能應用科技提升計畫中，成果斐然，技術移轉江陵機電生產新型的太陽能家用熱水器。

本人思索以往的太陽能應用技術，根據學理估算和研究經驗得出：用熱泵系統回收瓦斯廢熱的方式應該比純粹用熱交換器的回收率更高，只要有適當的設計和控制器，可以研究出一種結合瓦斯、熱泵、太陽能的複合式熱水器，具有高效率、加熱快的特點，更貼近國人的使用習慣，提高能源使用效率。這些目標在實驗中一一得到證實。

3. 研究方法

系統設計

本設計的特點在於將熱泵和即熱式瓦斯熱水器結合，使得高達攝氏 200 度的排氣下降到攝氏 50 度，抽走的廢熱則改去預熱冷水，達成提高能源效率和瓦斯減量的目標。新舊設計的差別之處請看以下的解說。

舊式的家用型即熱式瓦斯熱水器如圖 1 所示，這是目前市面上常見的，它的構造中並沒有熱水儲存桶。冷水流進熱水器時，先在燃燒室外壁上盤繞三圈預熱，然後到熱交換器加熱變熱水，熱交換器位在燃燒室上端，是鰭片式。熱水溫度和瓦斯流量及水流量有關，兩者相依。吹過熱交換器之後的瓦斯燃燒廢氣仍舊有非常高的溫度，實地測量高達攝氏 200 度，排放溫度太高，可見得瓦斯燃燒熱並沒有充分利用，有回收再利用的價值。排放到大

氣時的溫度若降溫到攝氏 40 度，代表瓦斯燃燒熱幾乎 100 %利用。

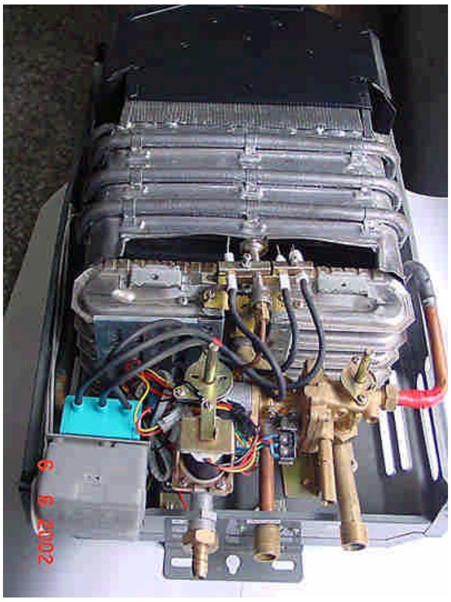

圖1 瓦斯熱水器內部構造圖

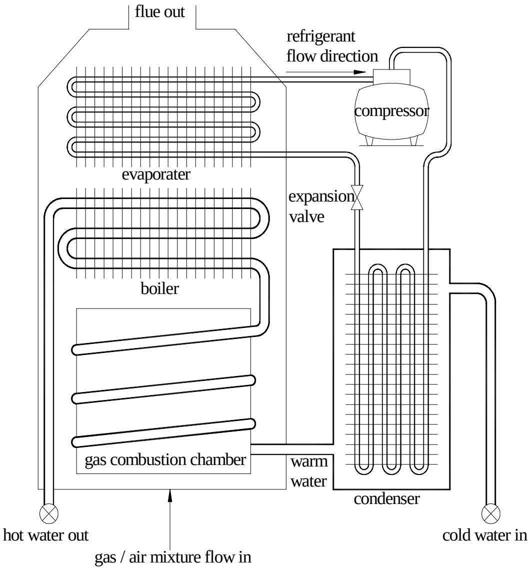

圖2 瓦斯熱水器廢熱回收架構

本計畫的新式設計如圖 2 的架構示意圖。在新設計的構造中，加入了熱水儲存桶。當冷水注入儲水桶內，先由冷凝器預熱成溫水，再流進瓦斯燃燒熱交換器內加熱成熱水，分兩段來加熱。冷媒進行熱泵循環，在蒸發器吸熱，在冷凝器放熱。熱泵循環（圖 2 的右半部）安排在瓦斯熱水器（圖 2 的左半部）旁，兩者並排，用來回收燃燒廢氣。蒸發器擺在排放燃燒廢氣的通道後端，冷凝器浸在儲水桶內，如此一來，燃燒廢熱被蒸發器回收，又被冷凝器排放到儲水槽內，冷水經過預熱後，瓦斯的燃燒熱能整體使用效率提高，用量就會減少。所以廢熱回收越多，代表瓦斯燃燒熱的使用率越多，就越省瓦斯。這就是燃氣熱泵熱水器。如果進一步結合太陽能，就是太陽能燃氣熱泵熱水器。

即熱型燃氣熱水器的流量

一個普通的即熱型燃氣熱水器，它所排放的廢氣溫度的廢氣至少在 100°C 以上，而且大多數時間在 190°C 上下，發展燃氣熱泵熱水器，必須先就即熱型燃氣熱水器回答以下三個問題：(1) 燃氣產生熱水的能力為何？(2) 有多少廢熱沒用到？(3) 回收了多少廢熱？這 3 個問題合起來提供燃氣熱泵的性能，很重要。即熱型燃氣熱水器的餘熱量必須確定之後，才知道該如何訂定熱泵的額定設計值。

即熱型燃氣熱水器可以產生熱水的能力，首要和燃氣流量有關。燃氣流量有個氣閥可以調節，調查觀念也就是問：在產生熱水的這段期間，共用去了多少的燃氣？

圖 3 刻畫出當氣閥固定在 3（最小流量），4（中間流量）、5（最大流量）這三個較明顯的位置時，用氣量和用氣期間的線性關係：如果氣閥固定在某一個刻度位置，燃氣用量和氣閥開啟時間成正比。而且燃氣閥門開到刻度 5 和 6 的位置時，氣流量沒有差異。當燃氣閥門固定位置不變化時，燃氣流量是個不會改變的常數，只要測量閥門開通的時間，就可以推算出用去了多少的燃氣。

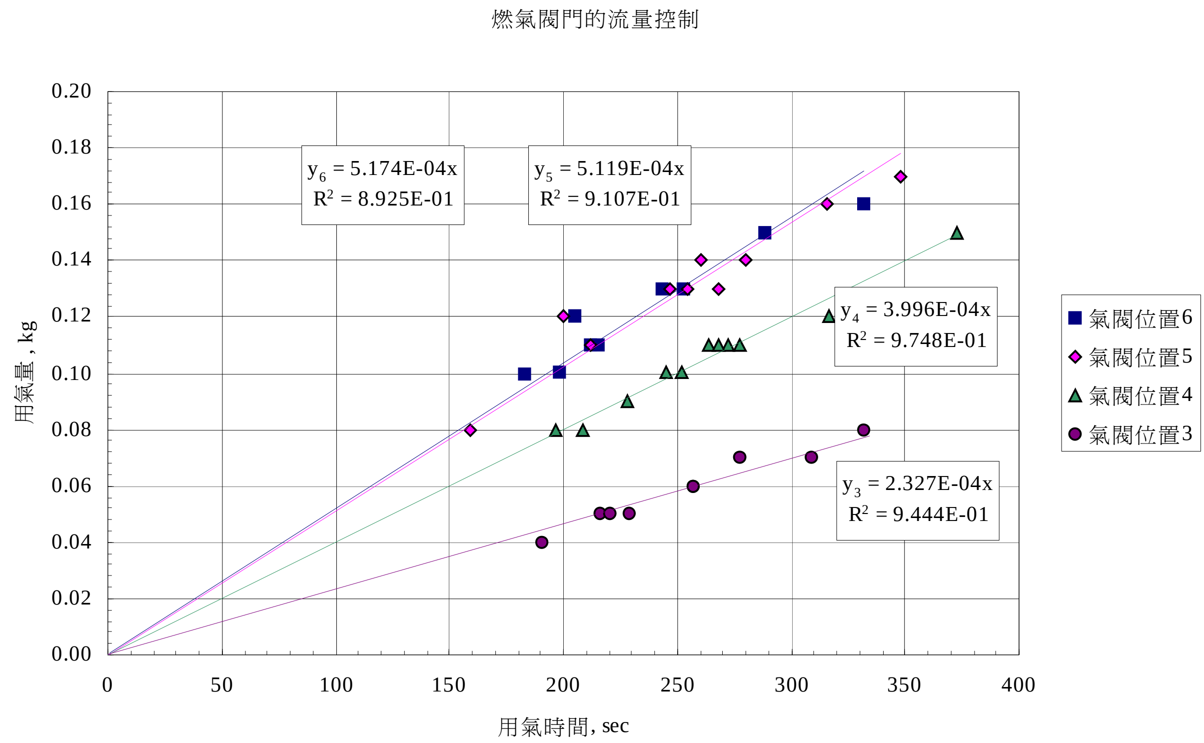

圖 3 燃氣閥門和用氣量的關係

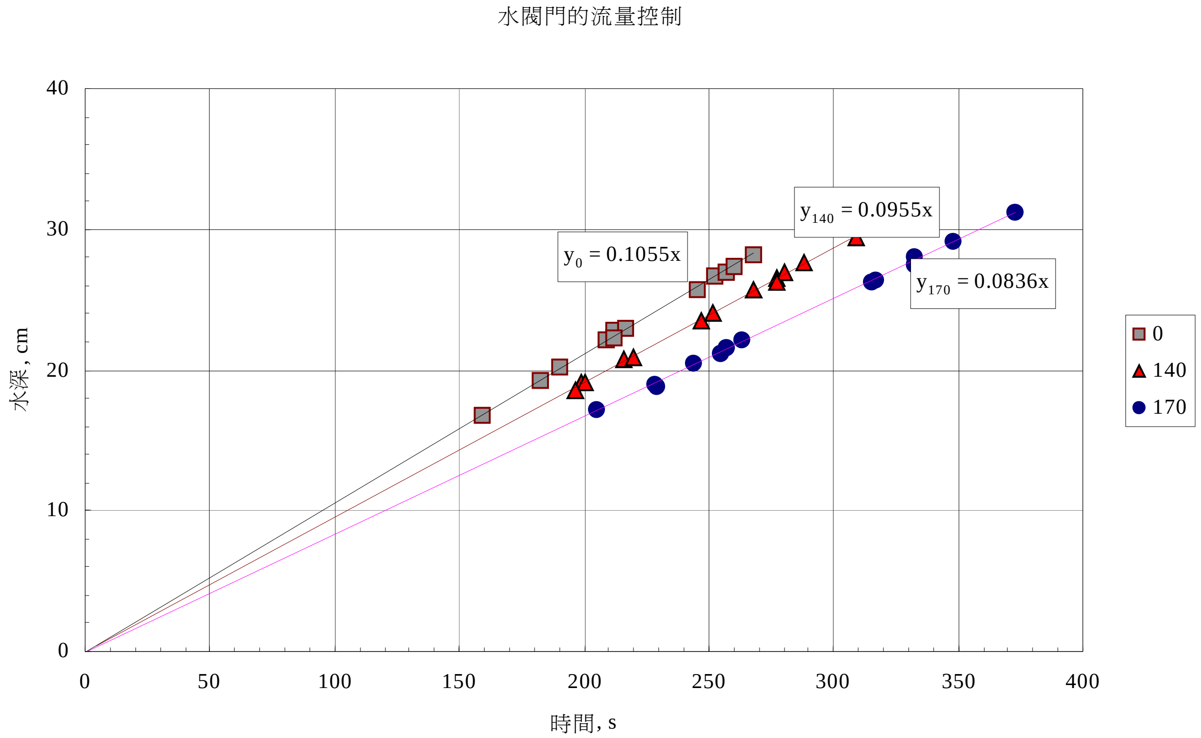

圖 4 水閥門和用水量的關係

使用即熱型燃氣熱水器時，氣閥位置決定了開大火或是開小火。當火力不變的情況下，而且進水的冷水溫度也不變，則水流量會決定出水的熱水溫度高低。水閥控制著水流量，有三個較明顯的位置，分別是最大流量（角度 0 度）、中間流量（角度 140 度）、和最小流量（角度 170 度），測量流量時，在進水上游裝了一具加壓泵，水的表壓大約從 1.8 到 2.2 kgf/cm^2，提供足量的水流和水壓進入熱水器，以預防空燒現象。

即熱型瓦斯熱水器產生熱水的能力如何？若不管氣閥和水閥的位置，只統計燃氣用量和水吸熱量，可畫成圖 5，圖中的線性關係也說明了兩者成正比，而且是固定比值。換言之，燃燒每公斤的燃氣，能夠被水吸收的熱量是固定不變的。故直接秤重燃氣的用量，就可以從圖 5 索引出水增加的熱量有多少。

因為水流在熱水器吸熱，燃燒熱轉化為內能，溫度變高。測量（1）加熱前的初始水溫、（2）加熱後的最終水溫、（3）水的質量流量，這 3 個條件代入（1）式，估算水吸收的熱量。

$$Q_w = \dot{m}_w c_{p,w}(T_{w,f} - T_{w,i}) \tag{1}$$

燃氣燃燒提供熱量，用氣閥調節燃氣流量，氣閥固定時流量固定，而燃氣流量和又和火力大小成正比，燃料用得多時火力大，燃料用得少時相對火力小，所以把燃燒的時間排除在外，從累積量的觀點換成氣閥流量的觀點，就變成水的加熱功率和燃氣流量之間的關係，如圖 6 所示。

因此，記錄氣閥位置就可以根據圖 3 估算燃氣流量，再從圖 6 找到水的加熱功率。流量的測量牽涉到計時器和重量計的解析度，碼錶的解析度高，可以取樣到百分之一秒，可是重量計的解析度只能到 0.01 kg，而燃氣重量的變化又很小，以現有設備只能做到如此。

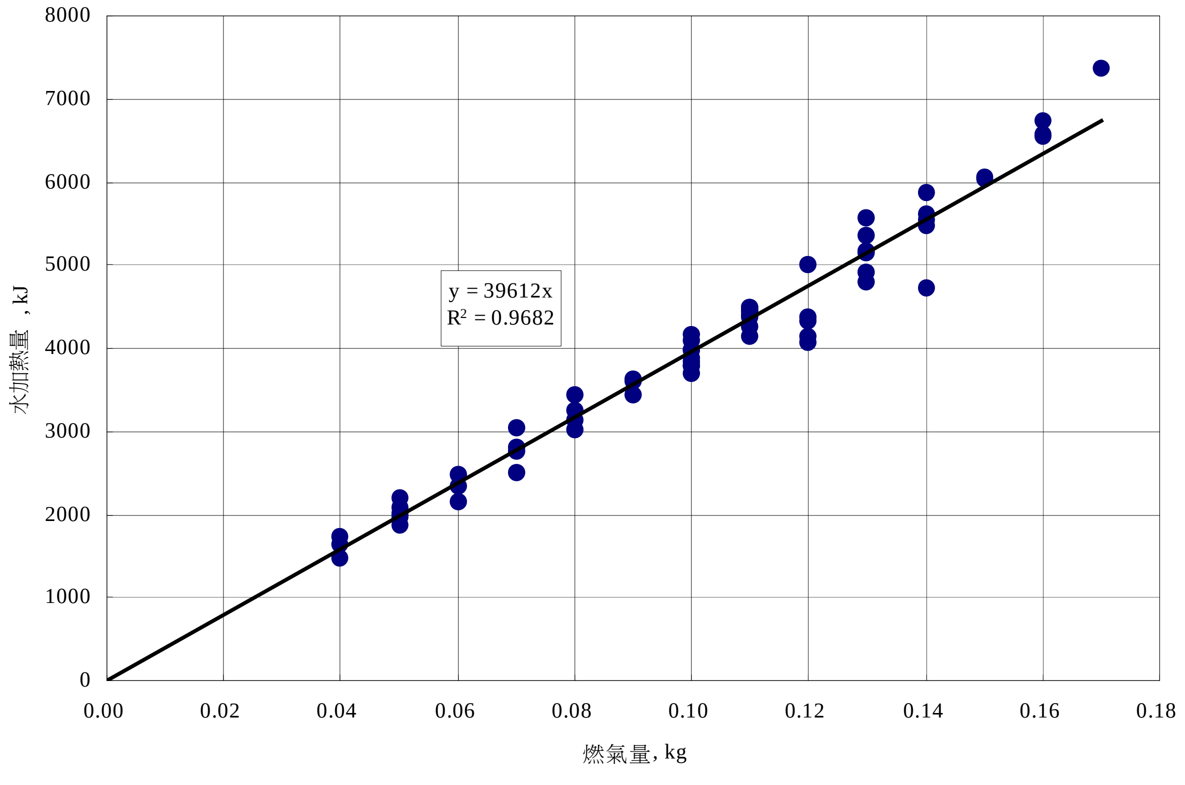

圖 5 燃氣用量和水吸熱量之間的當量關係

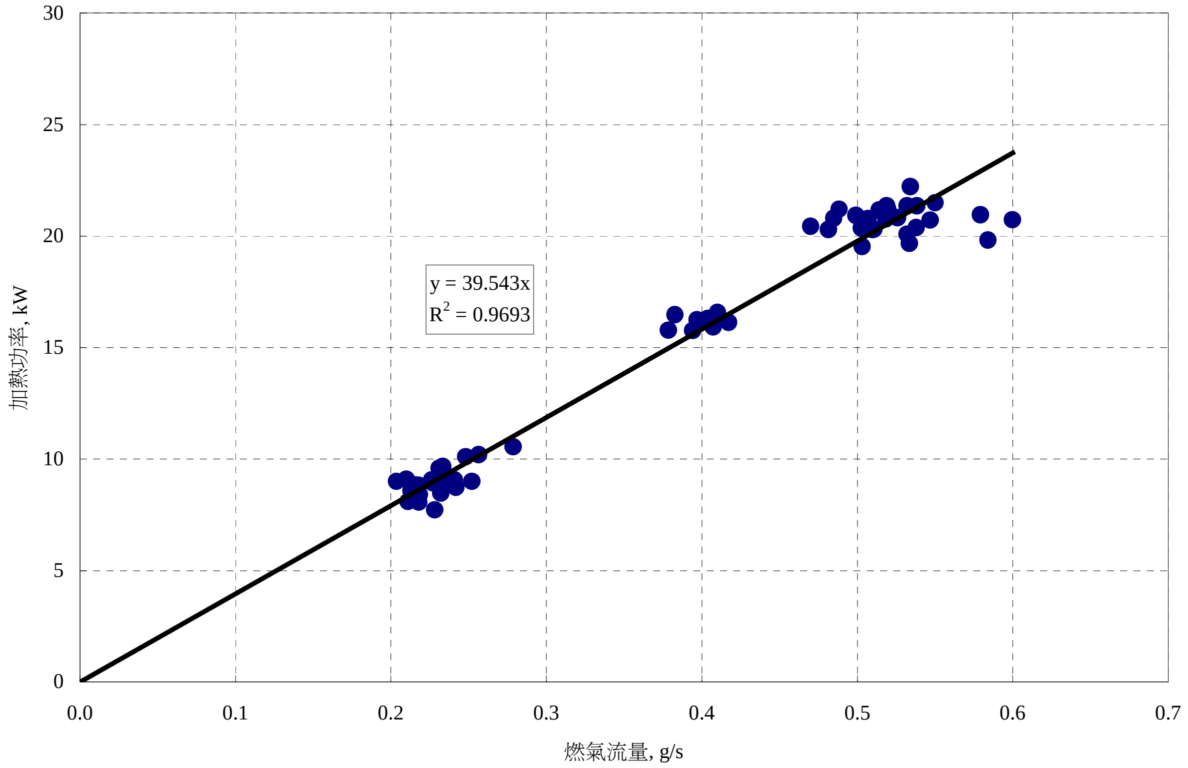

圖 6 燃氣使用率和水的加熱率之關係

即熱型瓦斯熱水器的廢熱

已知液化天然氣在完全燃燒時可放出燃燒熱約 50050 kJ/kg，當燃氣流量固定，可進一步算出在完全燃燒的狀況所放出的燃燒熱功率，其中水吸收走了多少的比例就是熱水器產生熱水的效率。結果如圖 7，說明水的吸熱量效率和燃氣流量不太相關。

圖 7 燃燒效率平均值大約為 79%，如果以煙道氣體分析儀所監測到的數據來看，燃燒效率大約在 81.9%左右。煙道氣體分析儀是消耗性器材，使用成本高，比較這兩種不同的方法，造成的效率差異如圖 8。以這個百分比來看，結果尚可接受，故可減少使用煙道氣體分析儀的次數。

燃燒熱扣除被水吸走的部分，剩下的廢熱將散逸到空氣中，燃氣用量大，散逸的也多，這是正常的概念，並不奇特。但是剩下的廢熱散逸掉的功率有多大呢？這個量卻和熱泵的規格有關。從圖 9 得知，廢熱功率約在 1 kW 到 10 kW 之間分布，和燃氣閥門的位置有關。當氣閥位置在最大處，則燃氣用量也大，廢熱的功率可以從 3 kW 到 10 kW 之間。最小的氣閥位置，廢熱明顯變少，分布範圍也小，從 1 kW 到 3 kW。

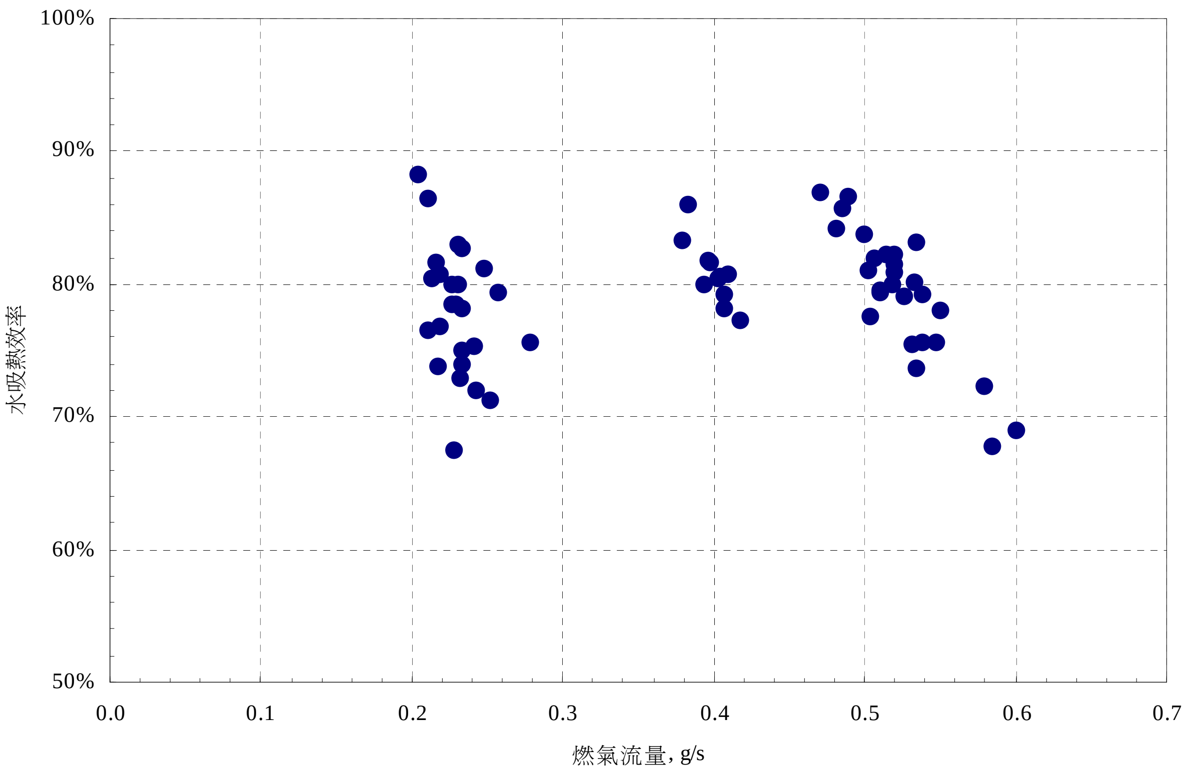

圖 7 燃氣加熱水的效率

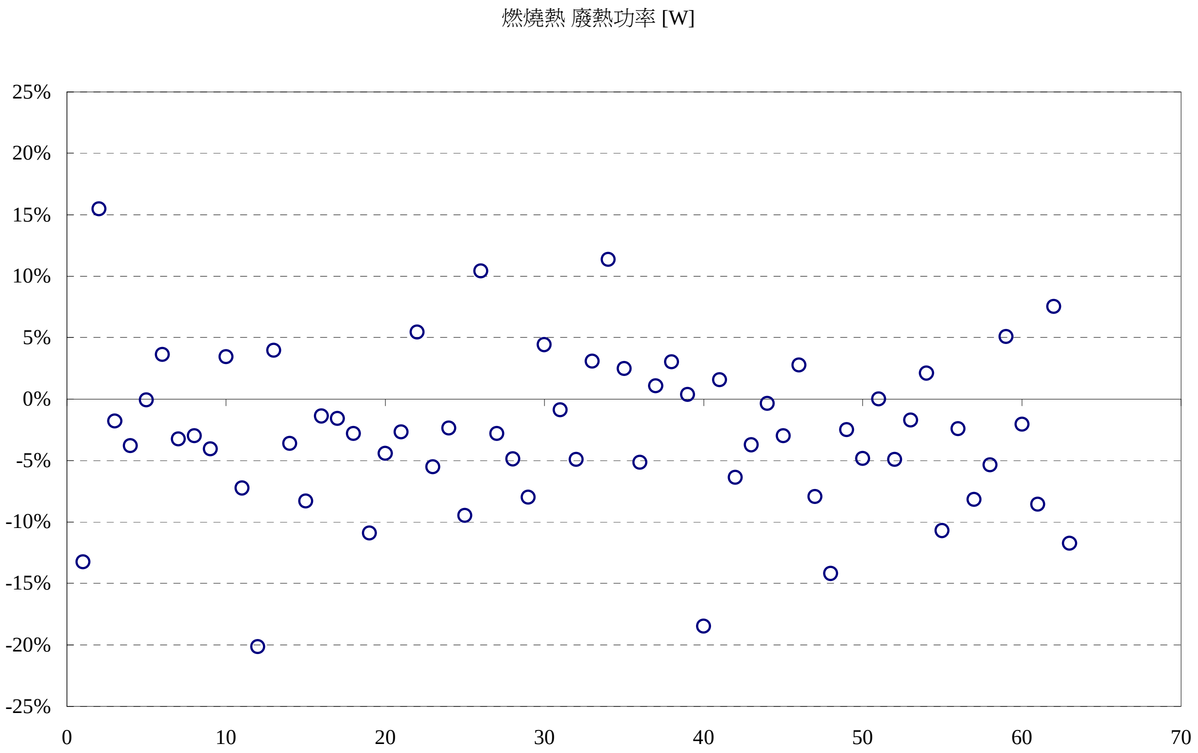

圖 8 燃燒熱使用效率之儀測和估算的差異

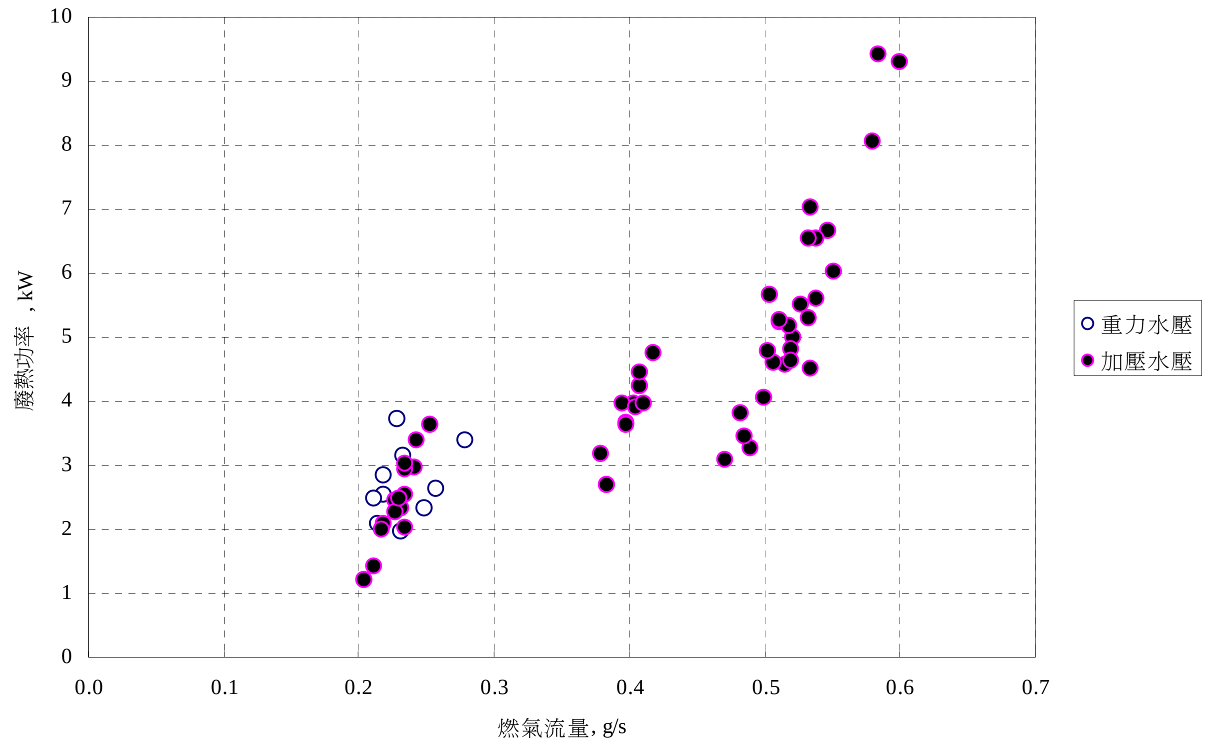

圖 9 廢熱測量分布

即熱型瓦斯熱水器的廢熱回收

對一個普通的即熱型燃氣熱水器，如果將燃燒廢氣導引到一個蒸發器，其內部充滿了液態冷媒，冷媒吸收廢熱蒸發成蒸氣，又被吸進壓縮機加壓，泵送到冷凝器去。冷凝器浸泡在冷凝水中，冷媒在這兒把吸來的廢熱交換給冷凝水後又凝結成液體，然後通過膨脹閥回到原來的蒸發器，完成一次冷凍循環。利用這種方式，究竟有多少的廢熱被回收了？

以圖 10 的狀況看來，當熱泵循環啟動之後，大約歷時 5 分鐘，進入穩定期間。屆時即熱型燃氣熱水器點火，30°C 的冷水吸收了燃燒熱，從熱水龍頭流出來的水有 65°C。熱水連續流了 14 分鐘，總共得到 4473 kJ 的熱量。與此同時，180 公升的冷凝水在 13 分鐘之內平均溫度從 30.7°C 上升到 32.6°C，增加了 1.9°C，合計下來冷凝水總共增加了 1430 kJ 的熱量，冷凝熱量包含了 289 kJ 的輸入電功，扣除後共回收了 1140 kJ 的廢熱。累積 COP = 4.95。換算成通量的概念，蒸發功率和冷凝功率分別約當 1.41 kW 和 1.76 kW。查閱圖 9，這個等級係落在燃氣流量較小的氣閥位置。

回收熱量（1140 kJ）約為熱水熱量（4473 kJ）的 25 %，換言之，有 25 % 的燃氣用量可以省下來。這個等級的廢熱回收量不算少，以先前推估的燃燒熱利用效率 0.79 來算，燃燒熱約有 5662 kJ，廢熱約有 1189kJ，而其中 1140kJ 的廢熱被回收了，換句話說，99 %的燃燒熱充分利用了，可說已經沒有任何的剩餘價值。

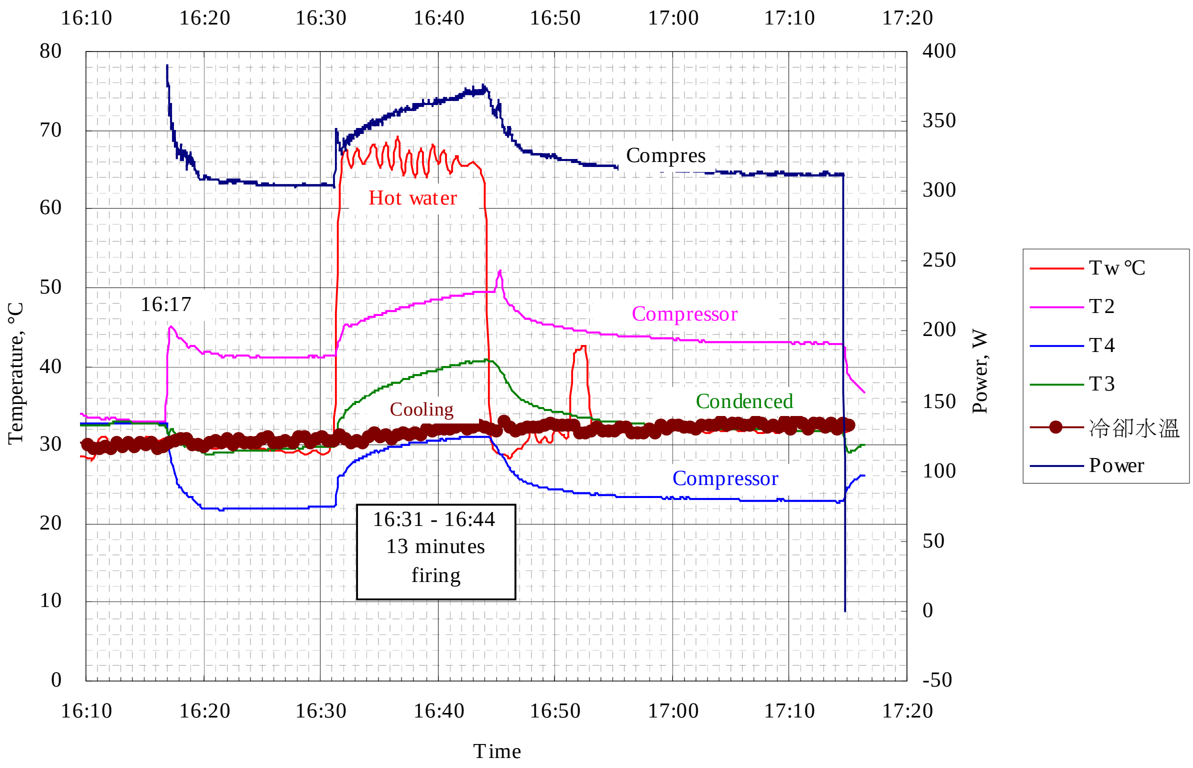

圖 10 即熱型燃氣熱水器和熱泵同時運作的操作情形

即熱型燃氣熱水器的廢氣分析

即熱型燃氣熱水器的廢熱呈現的現象可以用煙道氣體分析儀加以分析。首先值得注意的，莫過於危險性。在調查來的數據中，煙道氣體溫度和一氧化碳濃度最受關切。

當燃氣燃燒時間越久，煙道的溫度會越來越高。於是根據燃燒時間，把煙道氣體的溫度做成對應圖，如圖 11 的範圍，從 90°C 到 170°C 起，逐漸升高到 220°C，圖中並沒有待別把氣閥的位置標示出來，但燃氣流量越小，煙道的溫度也相對較低。這麼這的溫度，若是一不小心，有可能造成燒、燙傷。還好的是這些廢氣的量不會太多，只要下游數十公分遠，和環境大氣混合之後，很快就降到室溫了。相對可惜的是這些廢熱也隨之散逸到大氣中無法利用了。

另一個關切的事乃 CO 的濃度，觀察圖 12 中 CO 的濃度，似乎有些微的傾向於燃燒時間越久，濃度有下降的趨勢。反倒是 CO 濃度和過量空氣的關係，在圖 13 可以明顯的看出來。過量空氣也影響到燃燒效率，完全燃燒是在剛剛好夠的空氣時才會發生。過量空氣或不足量空氣，兩種情形都會使燃燒效率下降，如圖 14 所示。燃燒不完全，或是過量空氣太多，這兩種情形廢氣中都會有太多的氧氣，此時燃燒效率降低，如圖 15 所示。

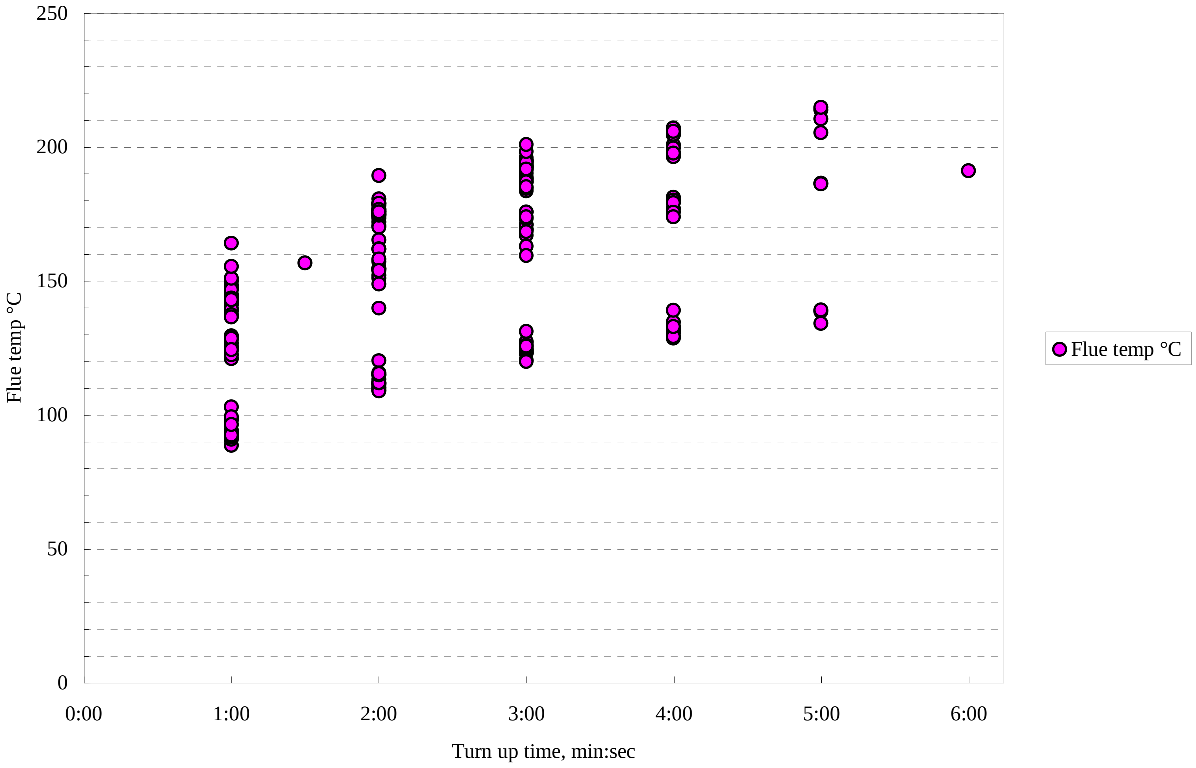

圖 11 煙道溫度和燃燒時間的關係

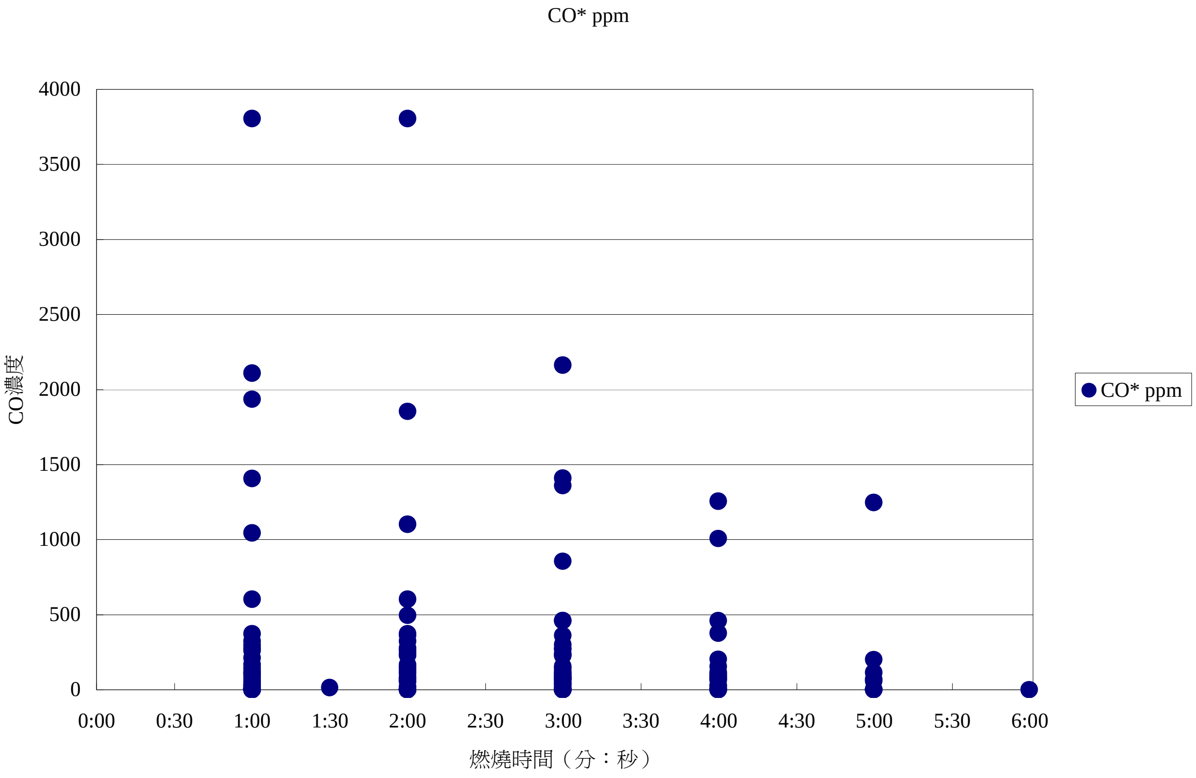

圖 12 CO 濃度和燃燒時間的關係

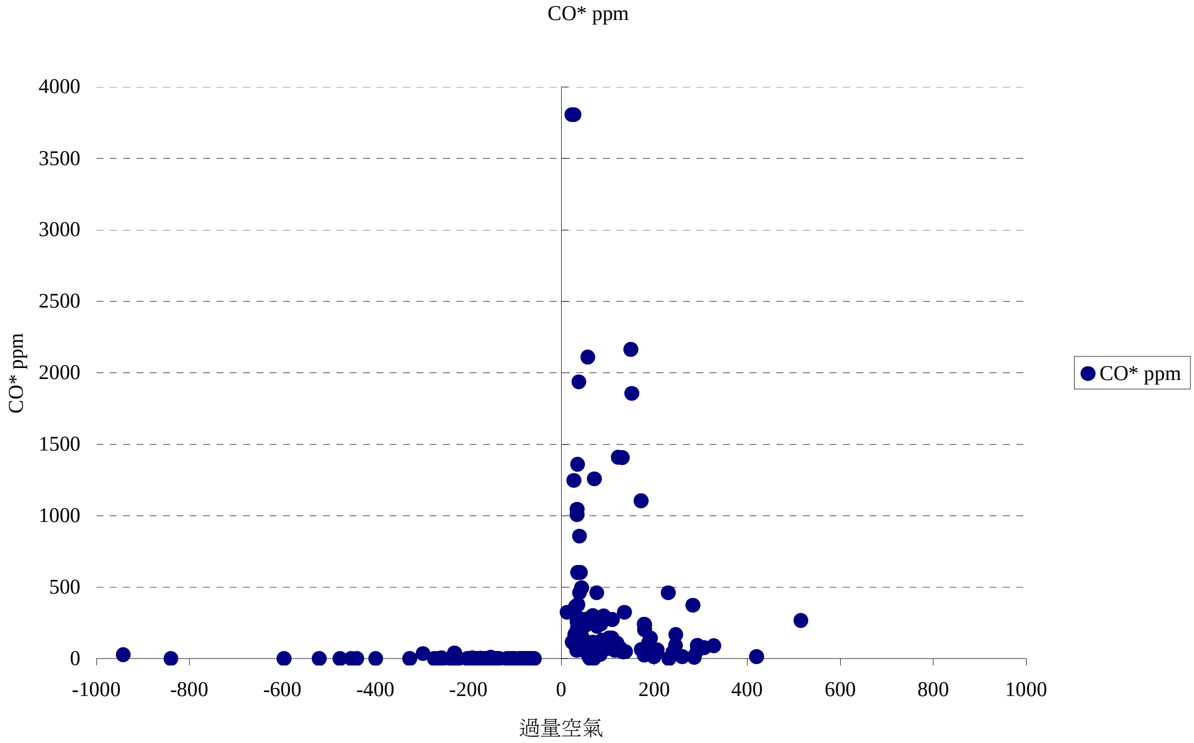

圖 13 CO 濃度和過量空氣的關係

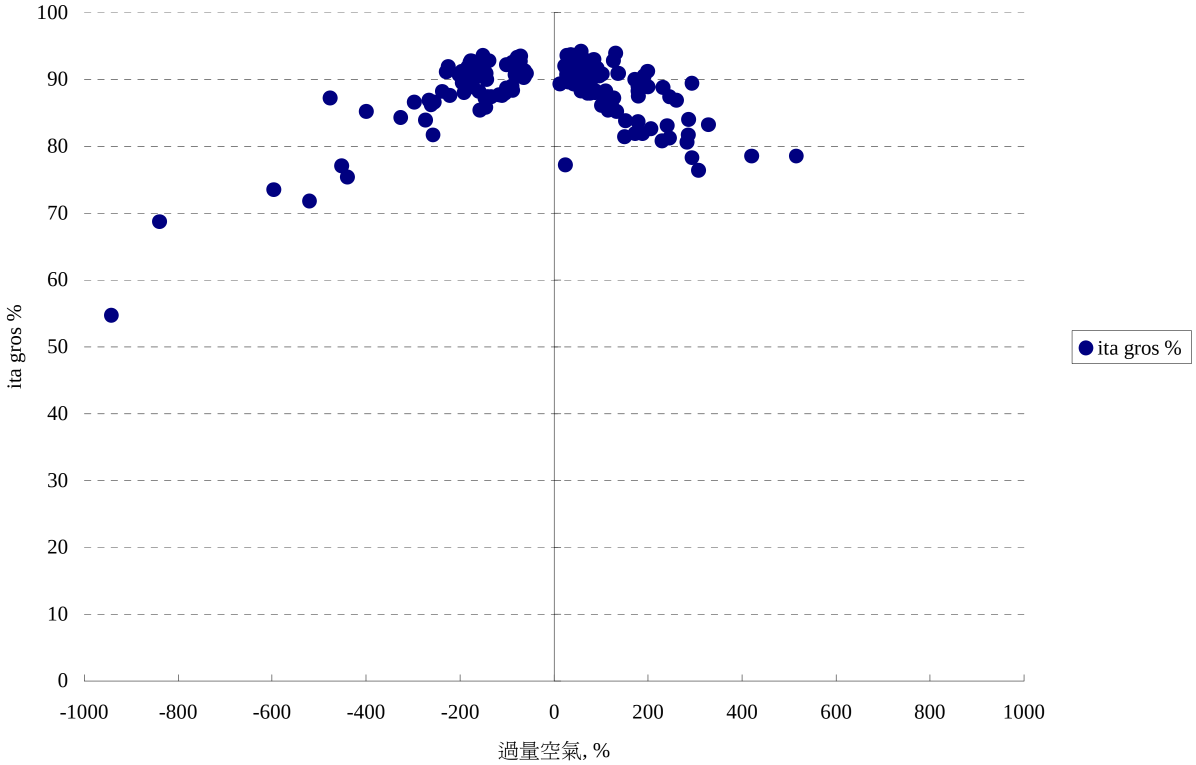

圖 14 燃燒效率和過量空氣的關係

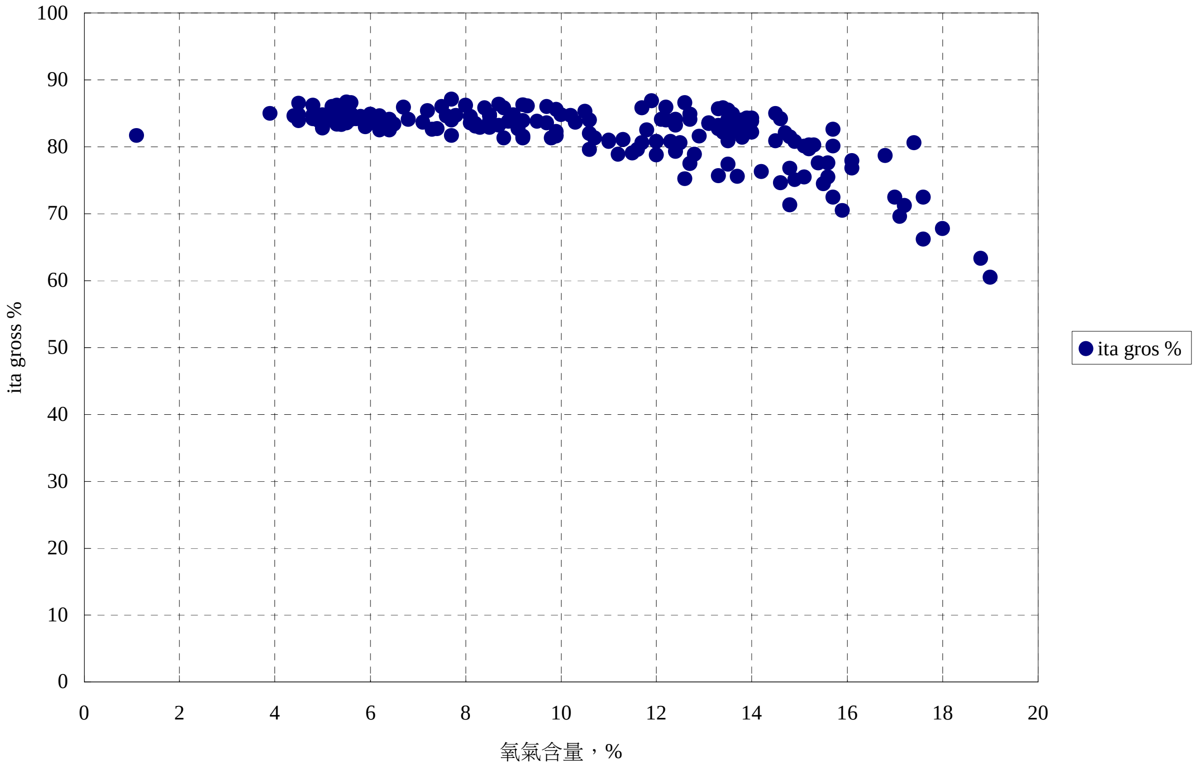

圖 15 燃燒效率和氧氣含量的關係

4. 結果與討論

蒸發器型式必須有足夠多的冷媒可以調節熱泵循環的平衡狀態。改良後的好處可以由操作情況證明：瓦斯熱水器點火操作連續 15 分鐘，在點火前為熱泵的平衡溫度，點火後約 13 分鐘，開始漸趨平衡，如圖 10 所示。

在廢熱回收方面，預熱的水溫持續升高，冷水預熱量和瓦斯加熱量的比例大約是 1:10。這是粗略估計，下一期將改變設備，量取更精準的數據。

因為本設計的一個特點在於太陽能並大氣取熱模式、瓦斯廢熱回收模式，兩種均可順利操作，若以目前使用的定壓膨脹閥來看，雖然勉強可以使用，但效果並不是很好，因為這兩種不同的模式都不能以最佳效率運轉。未來改良方向將以電磁控制式的可調定壓膨脹閥操作，維持最佳的系統效率，這在太陽能熱泵的實驗中曾獲得驗證。另一方面，若再搭配變頻壓縮機，將可獲得最佳化效率，是未來的發展方向。

本期研究計畫的實驗方面，已完成系統的穩定操作，實驗過程顯示這個新型熱水器操作現象複雜，兩段式加熱的預熱比因為冷水預熱而持續改變，所以系統是在動態擬平衡（dynamic quasi-equilibrium），蒸發溫度和冷凝溫度的平衡狀態持續而緩慢的改變。目前有自動化的溫度量測，但應加裝 pressure transducer，監控冷媒壓力的變化，尤其是在瓦斯引燃的全程中都應監控。熱泵是在擬平衡的情況下操作，系統有回授和時間延遲現象，這些都增加了研究難度。

研究至現在為止，重要的設計因數和其影響程度大致已找出來，但在實用化之前，仍必須先就操作控制做些實驗，例如當水溫漸高，熱泵的 COP 隨之漸少，操作成本墊高，應

有一個較適合的終止水溫，做為太陽能熱泵的停機指標，不足之熱水改由瓦斯加熱取得，此終止水溫尚待研究。又例如當用戶需要熱水時，而保溫桶內的水溫不足時，應從保溫桶內取出溫水加熱，而不是直接加熱自來冷水，但在不需要點燃瓦斯之時，通往瓦斯熱水器的閘門就要閉合。必須在操作控制研究完成之後，才能安心推出試用機型在市場上進行測驗。

從結果來看，結合即熱式瓦斯熱水器和太陽能熱泵所發明的新型的家用熱水器，除了維持立即提供熱水的服務之外，而且Energy Factor比之傳統的即熱式瓦斯熱水器更高。

如何設計一個好的瓦斯熱泵熱水器是研究重點。蒸發器效率扮演最顯著的角色，它的效率決定了有多少餘熱傳送到熱泵。採用好的熱交換器可以增進系統的Energy Factor到0.9以上。

預熱比的大小可能由系統自身能力自行調整，改良重點在冷凝器（預熱器），因為回收熱在此釋放到冷水中。以目前操作的實驗結果來看，瓦斯流量一直維持在小火，所以預熱比很小，預熱比（β）約為 0.1，故而系統一直維持在非常高的 Energy Factor。但在調整為中火和大火之後，預熱比將變大，冷凝器也相對重要起來。值得一提的是，熱泵的 COP 對性能似乎沒有什麼影響。

5. 參考文獻

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6. 計畫成果自評

結合瓦斯熱水器和太陽能熱泵的設計，從熱力學分析和實驗數據均證明可行，而且有很高的Energy Factor，已達成研究的初級目標。實驗顯示系統運作順利，而且國際上尚無相同的學術報告。

本研究具有學術和實用的雙重價值，屬於太陽能創新研究，成功後可望技術移轉開發商業產品。本計畫係結合理論和實務性質之應用性研究計畫，可增加技術研發經驗並提昇技術創新研發能力，且培育能源和系統控制的人員多人。與民間企業需求相符，滿足國科會補助研究計畫之精神。

附件一

可供推廣之研發成果資料表

■ 可申請專利　■ 可技術移轉　日期：97 年 10 月 28 日

國科會補助計畫	計畫名稱：整合太陽能暨瓦斯雙效輔助技術用於提升熱泵熱水器性能之研究 計畫主持人：秦政平 計畫編號：NSC96－2221－E－263－002－　學門領域：能源
技術/創作名稱	太陽能瓦斯雙輔助熱泵熱水器
發明人/創作人	秦政平
技術說明	本設計係用太陽能熱泵回收燃燒廢熱來預熱冷水，達到提高瓦斯燃燒熱能的整體利用效率，所以 Energy Factor 比傳統的瓦斯熱水器更高，瓦斯用量更省。而且新設計保有即熱式熱水器快速供應熱水的優點。 The new design has a heat pump used to preheat cold water with recovered heat from instantaneous gas water heater. Lump utilized efficiency of gas fuel combustion heat is improved with less fuel. Energy Factor is also higher than the traditional gas water heater. Fast hot water supply is also reserved.
可利用之產業及可開發之產品	重工業需求溫水。民生工業。 用熱泵回收廢熱的即熱式瓦斯熱水器。
技術特點	利用太陽能熱泵回收即熱式瓦斯熱水器廢熱的新設計，可立即提供熱水，而且提高瓦斯燃燒熱能的使用效率，瓦斯用量減少。EF 預估可提升到 0.9 以上，比傳統瓦斯熱水器更高，媲美電熱水器的程度。
推廣及運用的價值	1.　本設計切合國人的使用習慣，又節省寶貴的能源，降低瓦斯用量，因此氧氣的消耗減少，CO_2、CO 產生量減少，安全性提高。 2.　經濟上以熱泵熱水器為例，在台灣大學機械系黃秉鈞教授推廣之下，熱泵熱水器已有 8 億元年產值，預估本新設計推出產品之後，可望以該水準為目標。

※　1. 每項研發成果請填寫一式二份，一份隨成果報告送繳本會，一份送　貴單位研發成果推廣單位（如技術移轉中心）。

※　**2. 本項研發成果若尚未申請專利，請勿揭露可申請專利之主要內容。**

※　3. 本表若不敷使用，請自行影印使用。

Integration of Solar Heat Pump and Instantaneous Gas Water Heater

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1 Introduction

Since 1997 the integrated solar assisted heat pump (ISAHP) water heater has been built, it's the cheapest model for a whole year compared with the flat-plat solar one, the electric one, and the gas-fired one. Its installation has less restriction than the traditional solar one, but its heating time is still too long.

One of its new developments was to integrate an instantaneous gas water heater, as shown in Figure 1. While the stored water is not hot enough to afford user's demand, the instantaneous gas water heater lights up, at the meantime the waste heat in flue is recovered by the heat pump and turn to preheat cold water. Thus the user could have continuous twenty-four hours hot water supply at a lower level cost.

As you can see that how much does the heat contained in flue decide the capacity of the heat pump. But the solar energy that the collector/evaporator can absorb is another consideration when a system is designed. The dilemma could cause a serious problem while the system is operating.

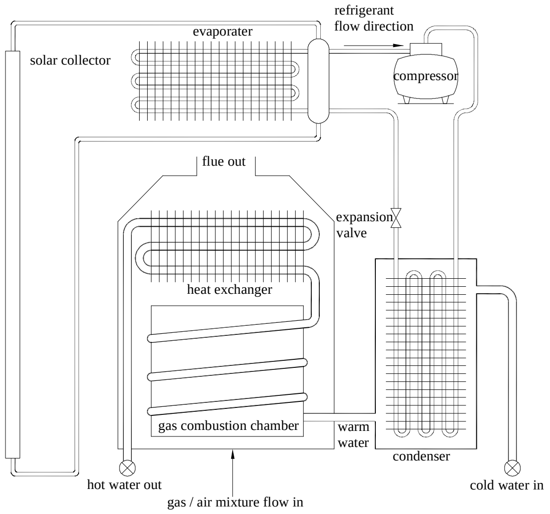

Figure 1. The integrated system.

2 Method

Capacity of the heat pump that can satisfy both the demands of incident solar energy and waste heat in flue is a key point for a successful design. Refer to the success of the ISAHP a heat supply with 500 kW is suggested.

A Rankine cycle was set up to collect solar energy, recover the waste flue heat, and change water from cold to hot at the condenser. It adopted a hermetic reciprocating compressor, a condenser, a constant pressure expansion valve, and a flooding type evaporator to form a 500 kW of refrigeration capacity system. High and low pressures of Rankine cycle were monitored with pressure gauges. Temperatures were measured with four T type thermocouples at the suction and discharge of the compressor, upstream and downstream of the expansion valve and were recorded with TESTO T177 data logger.

Cold water circulated from a 200 liters tank to the condenser in 18 c.c. per second driven by a pump. Thermocouples were set up to monitor and record the temperatures at the waterside inlet and outlet of the condenser, and the mean one of the tank.

Two DC fans 12 cm in diameter is placed next to the evaporator. A power supply drove them in 12 volts to make a forced convection that waste gas in flue was sucked and passed through the evaporator. Wind speed and temperature were both recorded. The waste gas was monitored using a flue gas analyzer, TESTO MX325. Liquid fuel consumption was also measured with a weight scale.

Compressor consumed electric power to start and run the Rankine cycle. A PROVA MW-01 power analyzer datalogger recorded current, voltage, phase angle, power and accumulated work.

3 Results

The ISAHP water heater has no particular problem, but the evaporator of fin-tube type caused a serious problem. Because refrigerant flow in the serpent tube of the evaporator caused nonhomogeneous evaporation, overheat at the suction line of the compressor increased gradually, when the instantaneous gas water heater was ignited. The waste heat in flue was still abundant so that the evaporator did not absorb it completely. The refrigerant reached quickly a superheated state 20°C higher than saturated temperature. At that moment fuel supply must be stopped right away because no sign showed increasing of overheat will stop. This dangerous condition was caused due to a wrong evaporator.

The efficiency of the instantaneous gas water heater is between 65% and 75%, shown in Figure 2. Experiments data are listed in Table 1. The residue of heat in flue, range from 3.17 kW to 4.17 kW, seems too huge, comparing to refrigeration capacity of the Rankine cycle. But the incident solar energy is about 1 kW/m^2 in average. Therefore, it is not possible to find a solution only changing a big evaporator. Finding another one with different type is suggested.

A flooding type evaporator was replace of a fin-tube one to protect the compressor. After it was replaced, the problem of non-stop overheat has been solved. This modification made the Rankine cycle can run 15 minutes at east without any damages and without overheat while the gas was burning.

The new integration system can sustain fifteen minutes operation. The piece of time is enough for most people when they take a shower. During this time the heat pump changes it heat source from solar assisted or air source to waste heat in flue. Because a large difference in intensity, equilibrium state of Rankine cycle shifted from lower pressure to higher pressure.

Testing results are listed in Table 2. The variation proceedings of the Rankine cycle and the water temperatures are stable, as shown in Figure 3 and 4. The sharps of temperature variations are fortunate similar to a RC circuit. This phenomenon implies that Rankine cycle is approaching a new equilibrium state. System could be stable again. No temperature of the Rankine cycle is exceeding 60°C when the fuel is burning.

While the instantaneous gas water heater was producing 42 liters of hot water from 28°C to 62.3°C, at the same time, 200 liters condensing water raised 1.5°C. The preheat energy is about 20 percent of the former.

The temperature of waste gas in flue was about 180°C. The same air passed through the evaporator and left below 50°C. It lost energy a lot. This implies that most of the waste heat has been recovered by the evaporator. In further if we compared these temperatures with the ambient temperature, the fuel combustion energy almost was in use. In other words, system has a high EF.

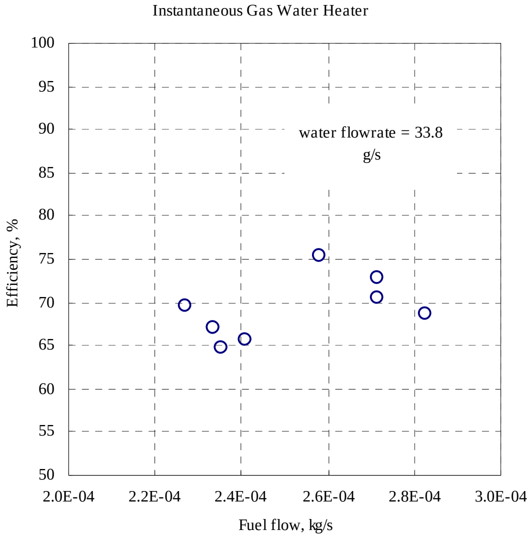

Figure 2. Test results of the instantaneous gas water heater.

4 Conclusions

The feasibility of integrating a solar heat pump and an instantaneous gas water heater has been proved. Flooding type evaporator is suggested. The instantaneous gas water heater can keep running 15 minutes at least in safe mode. This period could be enough for a hot water demand by user. High value of energy factor can be seen because the flue gas exited at 50°C. Those successful tests show 10 to 20 percent of gas fuel could be save.

Acknowledgements

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Table 1 Test results of the instantaneous gas water heater.

Water		Air		Flowrate		Combustion Heat	Water Heating	Efficiency of Water Heater	Heat in Flue
Inlet	Outlet	Room	Flue	Water	Fuel				
°C	°C	°C	°C	kg/s	kg/s	kW	kW	%	kW
19.5	75.4	22.1	165.1	0.0335	2.33E-04	11.68	7.85	67.16	3.84
19.3	74.4	22.2	166.8	0.0344	2.41E-04	12.06	7.93	65.78	4.13
19.2	73.7	22.1	166.8	0.0334	2.35E-04	11.77	7.62	64.78	4.14
19.5	75.5	22.3	166.8	0.0338	2.27E-04	11.36	7.92	69.70	3.44
19.1	88.3	22.6	184.0	0.0335	2.82E-04	14.14	9.71	68.70	4.43
19.9	88.6	22.9	184.8	0.0344	2.71E-04	13.57	9.89	72.89	3.68
19.9	88.4	22.9	185.1	0.0334	2.71E-04	13.57	9.58	70.61	3.99
19.8	88.7	22.9	185.7	0.0338	2.58E-04	12.92	9.74	75.42	3.17

Table 2. Instantaneous gas water heater lights up.

No.	Time	Refrigerant Temperature				Condenser		Cooling Tank	Hot Water Faucet	Compressor Power
		Suction	Discharge	Condensed	Expansion	Water Inlet	Water Outlet			
		°C	°C	°C	°C	°C	°C	°C	°C	W
1	16:00:39	24.5	45.9	36.3	26.7	36.7	40.4	36.8	59.2	370
2	16:01:39	28.0	49.3	40.3	29.0	37.1	41.1	37.1	61.5	358
3	16:02:39	29.0	50.2	41.4	30.0	37.3	42.1	37.2	63.1	364
4	16:03:39	29.4	50.6	42.1	30.4	37.7	42.9	37.1	64.4	368
5	16:04:39	29.8	51.1	42.8	30.8	37.4	43.0	36.7	63.9	371
6	16:05:39	30.1	51.5	43.4	31.0	37.1	43.6	36.6	61.4	373
7	16:06:39	30.4	51.9	43.8	31.2	36.6	43.3	36.7	60.5	377
8	16:07:39	30.5	52.3	44.2	31.4	36.6	43.8	36.9	63.4	379
9	16:08:39	30.7	52.6	44.6	31.5	37.6	45.1	37.1	63.9	380
10	16:09:39	30.9	52.8	44.9	31.6	36.6	44.4	35.9	62.0	382
11	16:10:39	31.0	53.1	45.2	31.9	37.6	45.5	36.7	61.8	385
12	16:11:39	31.1	53.3	45.3	31.9	37.0	45.3	37.7	61.9	385
13	16:12:39	31.2	53.5	45.6	32.1	36.7	45.5	37.7	61.9	385
14	16:13:39	31.2	53.7	45.7	31.9	37.4	46.0	38.3	62.5	389
15	16:14:39	31.3	53.5	45.6	32.0	36.7	45.3	37.7	63.3	391
16	16:15:39	31.3	53.9	46.0	32.1	37.0	45.8	38.4	61.5	386

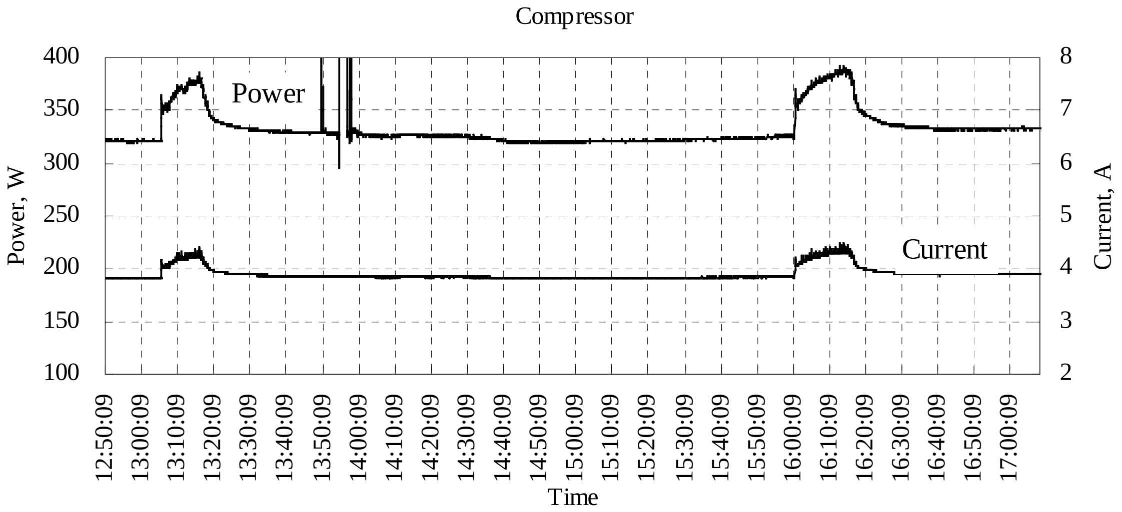

Figure 3. Proceeding of system test.

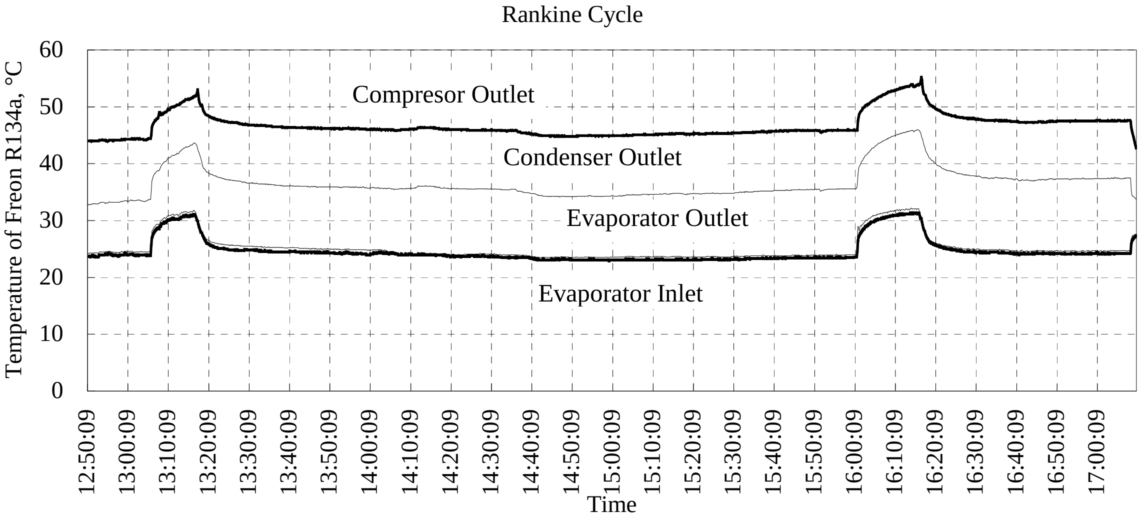

Figure 3. Proceeding of system test.

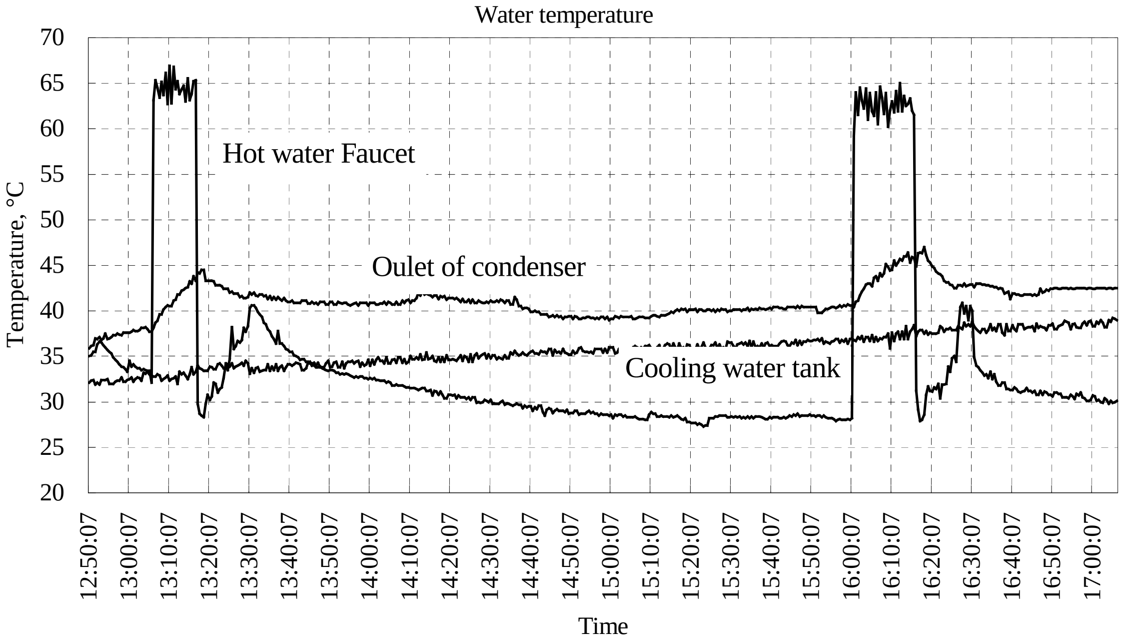

Figure 4. Proceeding of water change.

The Enhancement of an Integrated Solar Heat Pump with an Instantaneous Gas Water Heater

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1 Introduction

The integration of a solar heat pump water heater and an instantaneous gas water heater was proposed, built, and tested. Its success could create a new system that provides continuous twenty-four hours hot water supply at a lower level cost.

In spite of a high COP of the solar heat pump water heater, the stored water is not always hot enough to afford user's requests. While the situation occurs, the instantaneous gas water heater is light up. Meanwhile, some heat is recovered from the waste flue via the heat pump to preheat cold water.

A brief schematic of the new model is shown in Figure 1. Water flow first passes through the condenser then the instantaneous gas water heater, which is next to the solar heat pump water heater. Most combustion heat of gas fuel is exchanged to water directly. Some remaining heat is recovered at the exit of the flue by an additional evaporator of the heat pump. Heat pump preheats cold water at the condenser using the recovered heat and electrical work. Thus the fuel combustion heat is almost in use. Energy Factor (hereafter, EF) of the system could be enhanced.

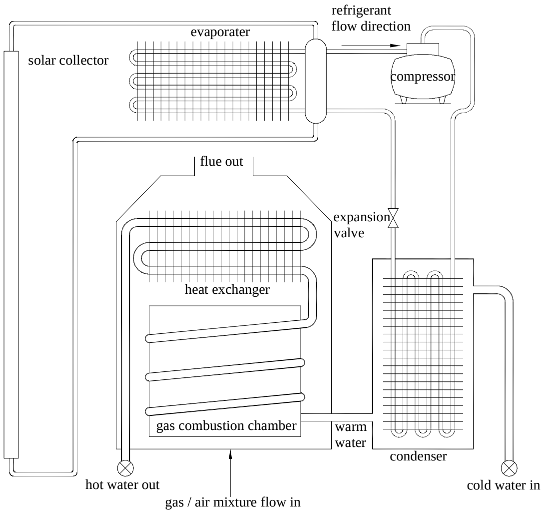

Figure 1. The integrated system.

A water heater's EF is defined as the ratio of energy gained to total energy input, as below.

$$EF = \frac{\text{water - heating energy}}{\text{total energy input}} \tag{1}$$

After building a prototype, experimental tests have shown its feasibility, however we still concern how much EF could it achieve, especial compared with other traditional domestic hot water heaters.

2 Methods

Clear drawing of energy flows in this system, as shown in Figure 2, indicates the feasibility when the instantaneous gas water heater is light up.

Releasing heat as gas fuel burning in the instantaneous gas water heater is named combustion heat, labeled as $Q_{combustion}$. As we known, more than half of it is transferred to water at the boiler, labeled as Q_{boiler}, remaining heat is called the residue heat, labeled as $Q_{residue}$. Equation (2) expresses the energy conservation.

$$Q_{combustion} = Q_{boiler} + Q_{residue}. \tag{2}$$

An efficiency of the boiler is defined as below, label as η_b.

$$\eta_b \equiv \frac{Q_{boiler}}{Q_{combustion}}. \tag{3}$$

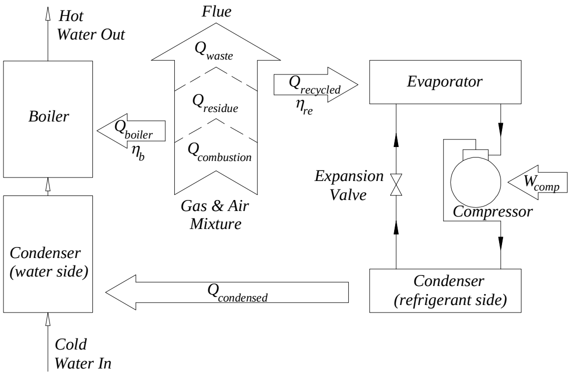

Figure 2. Energy flows in the system.

Because the heat pump recovers some residue heat, label as $Q_{recovered}$, with the additional evaporator, neither captured by the boiler nor by the evaporator is real waste heat, label as Q_{waste} . The energy balance equation is written as below.

$$Q_{residue} = Q_{recovered} + Q_{waste} . \qquad (4)$$

Efficiency of the evaporator, label as η_{re} , is defined as:

$$\eta_{re} \equiv \frac{Q_{recovered}}{Q_{residue}} . \qquad (5)$$

Since the heat pump connects the flue and water flow, it can preheat the entering cold water with its driving energy, label as W_{comp} , and its recovered energy. We got thus the energy conservation equation as below.

$$Q_{preheat} = Q_{recovered} + W_{comp} . \qquad (6)$$

The COP of heat pump is defined as:

$$COP = \frac{Q_{recycled}}{W_{comp}} . \qquad (7)$$

As mentioned water flow first passes through the condenser, then the boiler, we can express the water heating energy in Eqn. (1) as the sum of condensation heat and boiling heat, calculated as below.

$$Q_{water} = Q_{preheat} + Q_{boiler} . \qquad (8)$$

Preheating term on the right hand side of Eqn. (8) is an additional term, comparing with a traditional instantaneous gas water heater. So we define a contribution ratio, labeled as *β*, as the first term to the second term.

$$\beta \equiv \frac{Q_{preheat}}{Q_{boiler}} . \qquad (9)$$

The total energy input in Eqn. (1) consists of electric work and gas fuel burning heat. So the EF of this new model is rewritten as below.

$$EF = \frac{Q_{water}}{Q_{combustion} + W_{comp}} . \qquad (10)$$

Substituting from Eqn. (2) to (9) into Eqn. (10), a function was derived as below.

$$EF = \left(\frac{\beta + 1}{\beta}\right)\left(\frac{(COP+1)\cdot \eta_{re}}{COP + \eta_{re} + \eta_{re}(COP+1)/\beta}\right) \qquad (11)$$

This function can be used to predict the EF when an engineer designs a water heater such like the new model.

In the system there are four dominated elements, boiler, additional evaporator, condenser, and the heat pump. Their cooperation decides the EF of whole system when the gas fuel is burning. In which the condenser and the boiler are combined into a contribution factor.

3 Results

EF is a good indicator of efficiency for a domestic hot water heater and helps us to know its economic affect. Eqn. (11) can be applied to predict the EF. For the detail inspection of the derived formula its overall chart was plotted and shown as figure 3. This chart gives us the trend of the performance when we are choosing elements.

How about the performance of the new type water heater with hybrid heat resources? For example, a conventional gas water heater with an EF equal 0.7 has 30 percent of combustion heat that can be recovered, if it is retrofitted by a solar heat pump. Suppose an evaporator with 70 percent efficiency is adopted, only 9 percent of combustion heat is lost. If the heat pump has COP equal 3, that means compression work equal 7 percent of combustion heat must be included when EF is evaluated. So the total EF is 0.91 (=(0.91+0.07)/(1+0.07)). We can find out the same value from chart 3 using contribution ratio of 0.4 (=0.28/0.7), COP of 3, and ita of 0.7.

The EF in this example has an enhancement of 1.31 times of the original one and is approaching the electrical resistance type, a range from 0.7 to 0.95. Nevertheless, thermal efficiency of electrical power plant is merely around 0.3. So this new hybrid heat sources water heater can save significant fuel consumption. Enhancement value is estimated based on the gas water heater's EF.

Generally speaking, traditional gas water heaters have EFs between 0.5 and 0.6, maybe around

0.8 for some high efficiency models. Oil type ones are from 0.7 to 0.85. Heat pump types are from 1.5 to 2.0.

Given a glance at chart 3, the overall EF is 0.82 at least. It may occur for a poor gas water heater with EF equal 0.5, retrofitted with a good heat pump, COP=3, and a 70 % of recovered waste heat. Enhancement of EF is 1.64 times of the original one.

Enhancement of EF is due to the contributions of the heat pump and the recovered waste energy from flue. Modified EF is approaching to one an electric hot water heater owned.

In fact, according to the experimental data a pioneering prototype that a typical gas water heater, EF equal 0.7, is retrofitted with a heat pump has an enhancement of EF to 0.84.

Viewing the chart 3, we can understand the most significant role is evaporator because the EF decreases so big when a poor one is applied. Typical efficiencies of evaporators are from 0.7 to 0.9. A higher heat transfer efficiency of evaporator is suggested of course, for instance η_{re}=0.9.

The lines of high COP heat pumps are at the left of low COP ones because tiny compression work is needed. This causes a small contribution ratio. Fortunate, the variation of EF due to the performance of heat pump seems small that we need not take care of it so much. This point is very important because the heat pump changes mode from solar operation to waste flue heat operation.

The heating process is not a steady state when the instantaneous gas water heater lights up. It's worth to mention that Rankine cycle will be tuning automatically during the operation if system has enough capacity to afford the demand for mass flow rate of refrigerant.

4 Conclusions

The performance of an ISAHP (integrated solar assisted heat pump) can be looked up in academic papers, nevertheless, in this paper the thermodynamic analysis still gives us the EF prediction for the new system, while the hybrid heat resources are running at the same time. This helps us to know its economic affect.

The overview of system's EF tells us that:
1. most of available energy is really in use,
2. a good evaporator should be adopted,
3. the COP of the heat pump is not significant,

as concluded.

Acknowledgements

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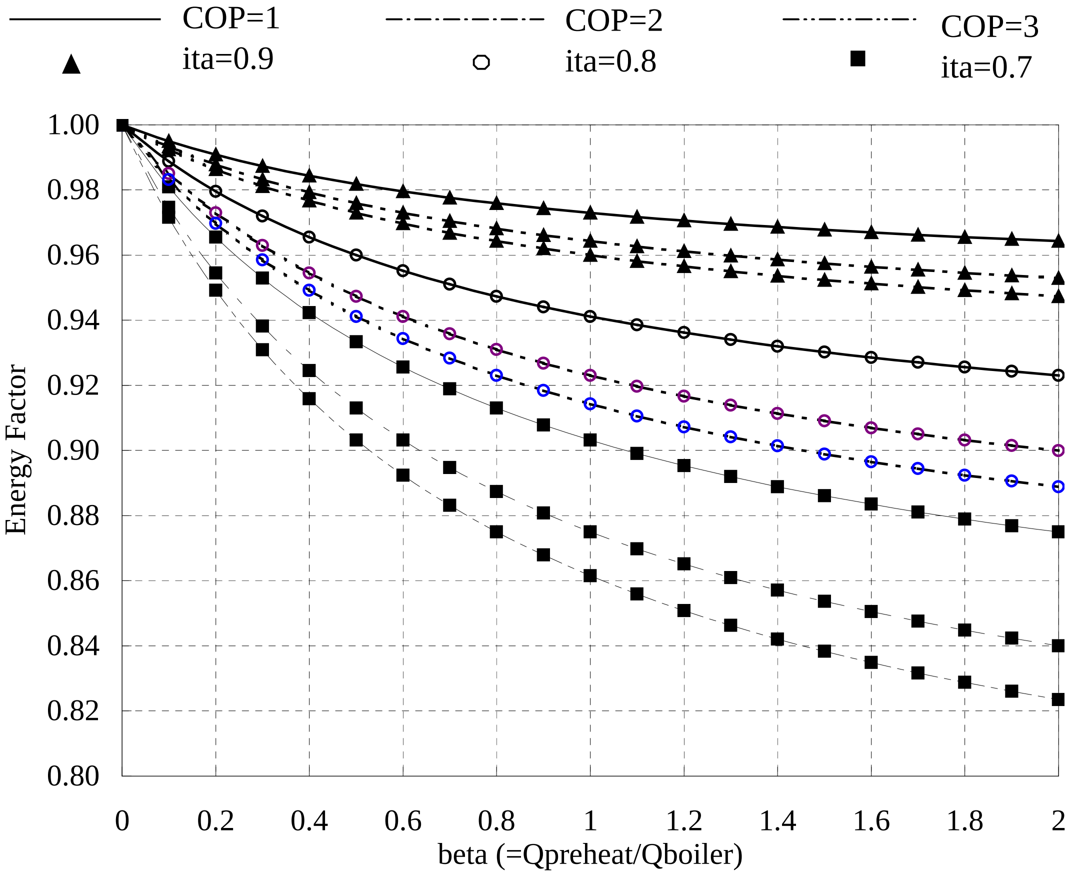

Figure 3. System's EF.