Tom Brooke, April 11, 2012

TODAY'S PARADIGM FOR AIR-TO-AIR HEAT RECOVERY

INTRODUCTION

1. This article supplements an Engineered Systems Webinar given April 11, 2012. Go to the archived version at http://www.esmagazine.com/events/559-today---s-paradigm-for-heat-recovery.

2. This article assumes a basic knowledge of how heat pipes work and HVAC air-to-air energy recovery systems. Consult www.heatpipe.com for further detailed information.

Technology advances! Just as commercial and industrial HVAC controls, chillers, and unitary equipment are constantly being improved, so too are the heat recovery systems used to recover heat (or 'cool') from a facility's exhaust air stream and transfer it to the incoming fresh air, thus saving energy. The term "heat" recovery (sensible heat transfer only) is specifically used to differentiate these AAHX[1] from those that transfer "energy" (sensible plus latent energy). But we shall see later that these traditional product categories are blurring as a more holistic approach is taken to reducing the total LCC for the owner. Further, the AAHX addressed here (Figure 1) are all constructed in the form of a chilled or hot water coil, as so common installed in Air Handling Units (AHU). To judge these advances, first this article will review building requirements as expressed in formal Standards and Codes for these (AAHX). Then four new or updated models of today's paradigm for selecting this equipment are discussed using the three 'E's of Effectiveness, Efficiency and Economics. Please note that unchanging aspects of this equipment selection, such as the good value of indirect evaporative cooling, are deliberately not addressed.

Often competing against other objectives, HVAC system designers are charged by their clients to minimize energy use. For IAQ reasons, minimum amounts of fresh outdoor air are mandated by code to be brought into buildings replacing exhaust air to dilute contaminants, and therein is the opportunity to use AAHX to reduce energy, or more precisely as we shall see, maximize their efficiency (maximum energy savings obtained at the expense of minimum energy used to obtain those savings). That need establishes the basis for the new first model of today's paradigm. The updated second model of today's paradigm recognizes that there are now many more physical forms of these AAHX, designed to fit many more building layouts, giving more freedom to the HVAC designer. The updated third model of today's paradigm illuminates the fact that not all geographical locations need total or enthalpic (sensible plus latent) energy exchange, and that the trade-off to use a sensible only AAHX is beneficial. Lastly, the updated fourth model of today's

Figure 1

[1] The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) uses the term AAHX to refer to all Air-to-Air Heat (and Energy) Exchangers

paradigm formally analyzes and makes a recommendation for the preferred technology when the supply and exhaust sections are separated but within 100 ft. of each other.

STANDARDS AND CODES

AAHX products are well defined by two different complimentary organizations: first, ANSI/ASHRAE Standard 84-2008 includes the product scope of wheels, pipes, plates and the runaround coil, and also sets the uniform test protocol for all AAHX. Second, ANSI/AHRI Standard 1060-2011[2] (also available in a SI version) includes the product scope of wheels, pipes and plates, defines nominal standard conditions for performance ratings, and conducts a third party certification program.

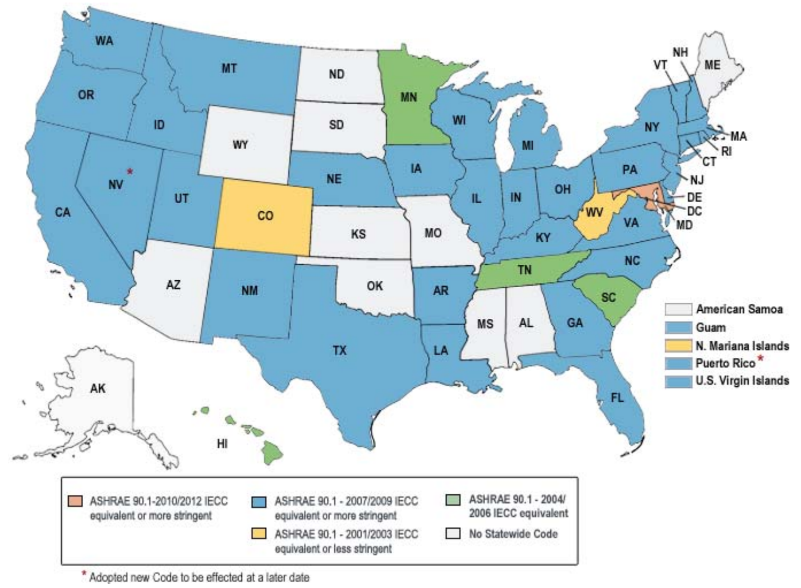


Figure 2

Under authority of the Energy Policy Act of 1992 approved by Congress, the application, use and design of AAHX in commercial buildings is governed by the Department of Energy through the International Code Council (ICC) and ANSI/ASHRAE Standard 90.1. The latest revision of Standard 90.1 is 2010 but the Department of Energy has one year in which to approve new revisions and the states then have two years to adopt the latest revision or justify why not. Considering lax enforcement, it is evident that there is a large time gap from when this important Standard is approved by ASHRAE to when it becomes legal enforceable Code in practice. The current (as of March 5, 2012) revision of the Standard adopted for each state is shown in Figure 2. Although there have been significant changes in each of the revisions, this article only addresses the 2010 revision.

AAHX systems are addressed in Sections 6.5.6 and 6.5.7. In a broad overview, there are three key components of this Standard:

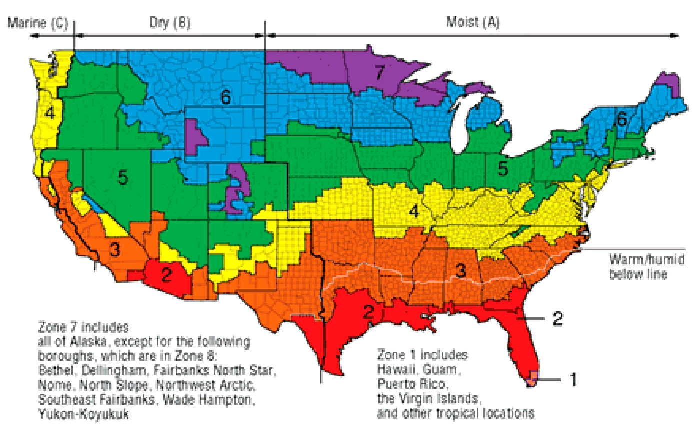


Figure 3

1. The requirement for their use is now keyed to the Standard's Climatic Zones shown in Figure 3. For example, heating recovery is not required in zones 1 and 2, but heating recovery is required for minimum Supply Air airflows (the minimum reducing in steps) as the zones get colder and/or the % of Outside Air/Supply Air rises from 30% to at least 80%.
2. Their design is specified to provide at least a 50% <u>enthalpic</u> Effectiveness. We'll dig further into this a little later.
3. However, there are ten general exceptions to the mandated use of AAHX as above (for example, laboratories and kitchens are allowed 50% and 40%

[2] ANSI/AHRI Standard 1060 is available as a free download at http://www.ahrinet.org/hvacr+industry+standards.aspx

respectively <u>sensible</u> Effectiveness, those areas with toxic, flammable and corrosive fumes are excused totally, etc.).

One further note on building codes: on a voluntary basis, the U.S. Green Buildings Council's Leadership for Energy and Environmental Design (USGBC LEED) program has more robust provisions than the Department of Energy. These requirements are specified in ANSI/ASHRAE 189.1-2009, Section 7.4.3.8.:

1. Energy recovery is required down to a 10% level of OA.
2. A 60% enthalpic Effectiveness is required.
3. No exceptions are listed.

<u>THE PARADIGM'S FIRST MODEL (NEW)</u>

Effectiveness has been a valuable and the primary measurement of the performance of AAHX for decades, with the associated airside pressure drop being secondary. The Effectiveness is a percentage of the actual amount of energy captured compared to the theoretical limit and is more precisely defined in ANSIAHRI Standard 1060. It can be established for sensible, latent and/or total (sensible plus latent) energy exchange, but if measuring sensible exchange, caution should exercised that no condensation is occurring on any heat exchange surface.

Seasonal EER, EER, kW/ton, etc, are measures of Efficiency long used in the Unitary and Applied HVAC sectors, and define the equipment's BTUH rating divided by the equipment's energy use needed to obtain that rating. In 2003, along those same lines, AHRI released Guideline V which added the equally fundamentally important definition of Recovery Efficiency Ratio (RER), defined as the energy saved divided by the energy used. RER recognizes that two different AAHX system designs may each provide the same effectiveness but one will provide a superior efficiency because it does so using less energy. It takes into account all the energy used to obtain the heat transfer, because just as AHRI includes peripheral energy consumers in the definition of EER and kW/ton, so too does RER for AAHX include peripheral energy consumers beyond just the airside pressure drop, such as wheel drive motors, purge losses (by using the reduced airflow rate to calculate the saved energy), and pump HP in the case of runaround coil systems. Its term is dimensionless except when the AAHX is combined with the primary equipment (say, RTU), whereupon it's expressed in EER units. And, just like Effectiveness, it can be defined for sensible, latent and total Efficiency. We will use Effectiveness and RER shortly to compare some systems.

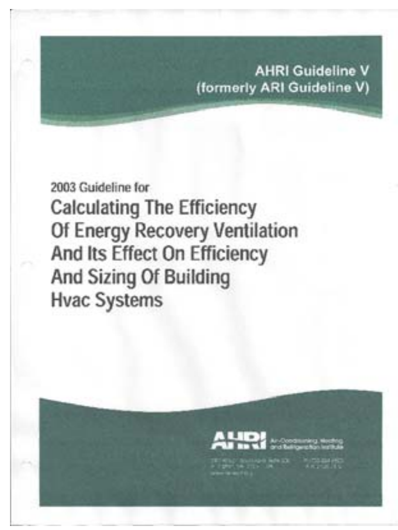


Figure 4

Adding the Efficiency metric to an AAHX's evaluation criteria is the paradigm's first new model. Now, heat transfer and pressure drop are inexorably linked. Sure, the system designer has always specified both the heat transfer and the pressure drop, but:

1. when the serious negotiations began, the pressure drop often was delegated to a secondary role because the rational was that there was enough safety in the selection of the fan and motor to accommodate an increase in the heat recovery pressure drop because after all, the incremental increase was only a small portion of the total pressure differential the fan sees; of course, this falsely penalizes an alternate selection with a higher RER.

2. Now the energy usage also must account for the sometimes substantial effect of parasitic energy losses when all initial system designs are being considered.

THE PARDIGM'S SECOND MODEL (UPDATED)

Architects take the lead in building design and sometimes heat recovery is not at the forefront of their thoughts. While the need for heat recovery is per code, sometimes a building design must be compromised to allow the use of the traditional heat pipe heat recovery system. The traditional system must have the Outside Air (OA) and Exhaust Air (EA) ducts in a counter flow (opposite) configuration, and they must be adjacent.

So the paradigm's second model is that today there are many more physically available types of heat pipe heat recovery systems. No longer are the airstreams required to be adjacent and counter flow; now they can have parallel airflows and can even be separate (Figure 5) while the owner still benefits from the performance and simplicity of heat pipes. End result: more favorable (including economic) building layouts!

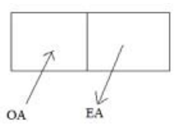
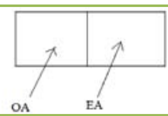
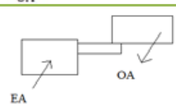
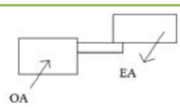
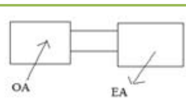
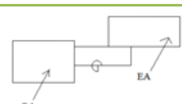
Heat Pipe Configuration	Airstreams	Airflows	Applicability
	Adjacent	Counter Flow	Winter Summer
	Adjacent	Parallel Flow	Winter Summer
	Separate (up to100' H, 50' V)	Counter, Parallel Flow	Winter
	Separate (up to100' H, 50' V)	Counter, Parallel Flow	Summer
	Separate (up to 40' H)	Counter, Parallel Flow	Winter Summer
	Separate (up to 100' H, 30' V)	Counter, Parallel Flow	Winter Summer

Figure 5

The first layout shown is the adjacent, counter flow heat pipe, traditionally the only design available. It features the lowest cost and highest available heat transfer. When installed level, maximum heat transfer occurs in both winter and summer and there is no need for a tilt or other seasonal control mechanical device. Thus, this heat pipe system truly has no moving parts and is the ultimate in reliability.

The second AAHX shown is the heat pipe designed for adjacent but parallel airflows. While it has a slight cost premium over the standard design, it has state-of-the-art internal circuitry that improves the performance far beyond that of a standard heat pipe installed in a parallel flow application. It's also designed for both winter and summer operation, and has no moving parts.

The third and fourth arrangements are called split, passive and allow the OA and EA ductwork to be separated, with one vertically higher than the other. To maintain the simplest operation with no moving parts, the higher heat pipe must be the condenser portion where the heat picked up by the lower heat pipe is rejected to the upper heat pipe's airstream. Thus, winter operation (in the northern hemisphere) is only available when the OA is higher than the EA, and vice-versa.

The fifth arrangement, also called split passive, provides winter and summer operation when the separated heat pipes are installed at equal heights.

If space is available, dampers are recommended for economizer and frost control for all the systems above, because bypassing air results in less airside pressure drop. However, when the space for dampers is not available, advanced stepper modulating valves that control the internal refrigerant flow and draw no power except when adjusting are available for those duties.

The last arrangement features fractional horsepower, magnetically coupled, industrial pumps controlled by variable frequency drives. The pumps allow further distances and winter/summer operation with any relative mounting location, and are used for economizer and frost control.

Now that we've learned about the importance of the Recovery Efficiency Ratio, let's use that (in addition to Effectiveness) to examine in Figure 6 the performance of each of these systems. All details of the typical design criteria used in determining the results are listed in the Appendix.

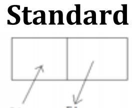
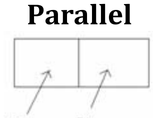
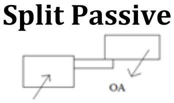
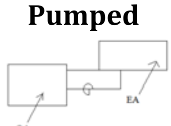
Heat Pipe Configuration	MBH Transferred	% EFFECTIVENESS	Airside PD " (Each)	Recovery Efficiency Ratio
Standard 	314	56	.56/.60	42.6
Parallel 	228	41	.56/.60	30.9
Split Passive 	255	45	.56/.60	34.6
Pumped 	287	51	.56/.60	28.9

Figure 6

Finally, we look at the last of the three "E"s … Economics. We first turn to ASHRAE's Climatic zones of North America as shown earlier. Because the geographical location will have a large impact on the economics, the procedure is to first pick a representative "average" North American location for heat recovery. Since these are sensible AAHX, we can ignore (for now) the letter designations within the zones that indicate the moisture aspect. Referring to Figure 7 and recognizing that winter heat recovery is far more important than summer recovery, Chicago in Zone 5 is a good, representative selection.

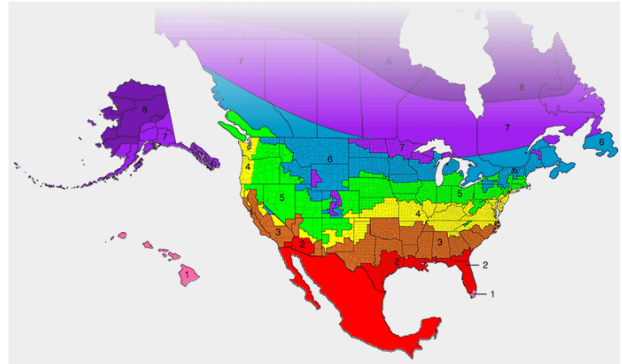


Figure 7

With the design criteria listed in the Appendix, the economic results for the four types of heat pipe systems are shown in Figure 8.

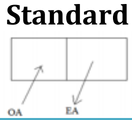
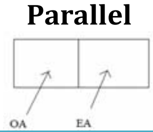
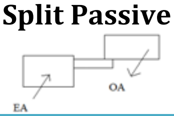
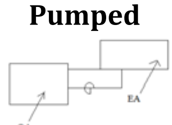
Heat Pipe Configuration	Capital Cost $000	Annual Maintenance Cost $000	Annual Energy Saved $000	Twenty Year LCC (Savings) $000
Standard 	21	1.3	17	+210
Parallel 	24	1.3	13	+148
Split Passive 	46	1.3	14	+143
Pumped 	87	1.6	15	+118

Figure 8

The traditional adjacent, counter flow heat pipe design has the best Effectiveness, Efficiency and Economics. While at the bottom of the Effectiveness ratings, the adjacent, parallel flow heat pipe design has the third place Efficiency and second place Economics. Even with the separation, the split passive design nearly equals the parallel Life Cycle Savings. Finally, even with the nearly doubled capital cost, the split pumped heat pipes turns in an impressive six figure twenty year Life Cycle Savings for those owners that can financially look long term.

THE PARADIGM'S THIRD MODEL (UPDATED)

The third model recognizes that heat pipes may selectively replace enthalpic AAHX. That's an aggressive statement, so what is its basis? First, we have to deal with the basics, the codes … ANSI/ASHRAE Standard 90.1 mandates a 50% enthalpic Effectiveness but the traditional heat pipe was shown at 56%, as seen in Figure 9. So what's the solution? Simple! Just use 8 rows and design for 350 FPM instead!

Rows	FPM	Sensible Effectiveness	Total Effectiveness	Total RER
6	500	.56	.41	42.6
8	350	.68	.50	68.3

Figure 9

Second, we've seen how ANSI/ASHRAE Standard 90.1 breaks North America into eight climate zones distinguishable by temperature. Many are then further broken down by Moist, Dry and Marine moisture levels. These differentiators are important because they recognize the wide variety of Outside Air design conditions. So let's just consider San Francisco as an example. Figure 10 plots the distribution of the hourly BIN data, coded by color, on a psychrometric chart[3]; these are the outdoor conditions. Also, the ideal human comfort range, as specified by ANSI/ASHRAE 55, is described by the parallelogram outlined in red; these are the indoor conditions. Certainly the outdoor dry bulb temperature must be and is addressed by the sensible heat pipe heat recovery systems to bring them within the dry bulb comfort range.

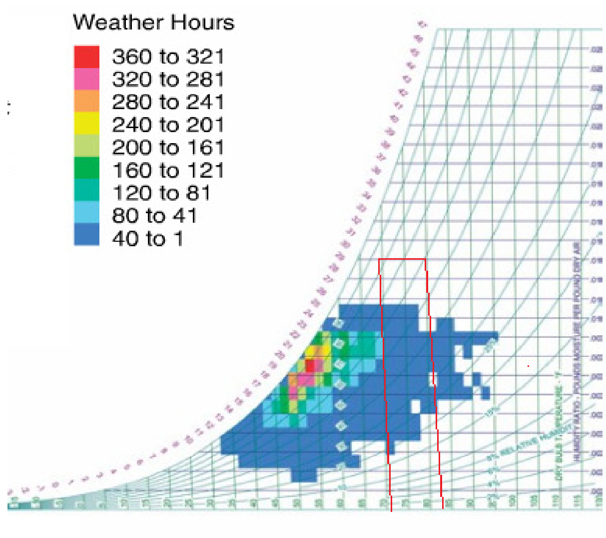


Figure 10

We can also see that the humidity, as expressed by the vertical axis, of the outside air is already totally within the vertical range of the comfort standard. While the comfort range shows no lower limit for humidity (as would be seen in the winter), in practice there are non-comfort factors that should be considered like static electricity and drying of the eyes. On the other hand, we can see that the natural outdoor winter moisture level plus the moisture given off indoors by people will provide at least a minimum indoor moisture level. Since there is then no need for latent (moisture) exchange from the exhaust air (EA) to the incoming OA, a heat pipe can just be used to transfer heat (from OA to EA in the summer and from EA to OA in the winter) rather than an enthalpic device with its contamination and complications.

[3] Hydeman, Mark. April, 2010. Take Care of the Money Sensors. Consulting-Specifying Engineer.

But why would one want to do that? So the third consideration of this model is that there are substantial benefits of heat pipes over enthalpic devices. Some of the benefits include:

1. No Moving Parts[4] so they are inherently more reliable with no emergency breakdowns and less maintenance
2. Fan Location is Not Critical[4], and there's no possibility of cross contamination for the exhaust air to the fresh air
3. Allowable Pressure Differential up to 55 in[4]
4. More Compatible with AHU Geometry, with standard rectangular coil construction and the complete cross sectional area is functional
5. No Electrical Connections

This third updated model of today's paradigm will be examined in detail in future articles.

THE PARADIGM'S FOURTH MODEL (UPDATED)

We shall see that after appropriate investigation, the run around coil should be replaced by the heat pipe whenever the distance between the OA and EA locations is less than 100 ft, and that is the paradigm's fourth model.

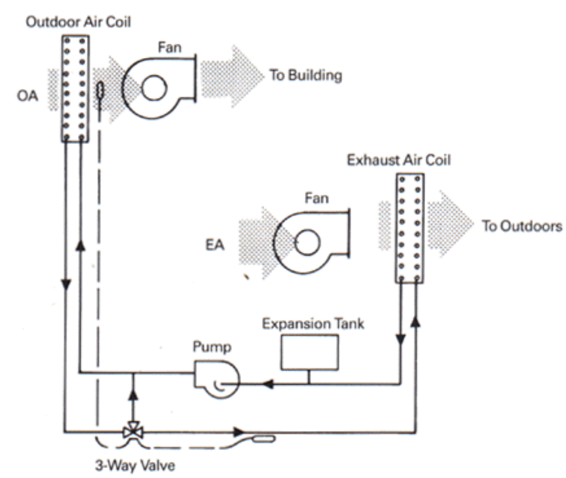


Figure 11

The coil runaround loop uses typical finned tube water coils, with construction materials modified as required for the application, installed in each of the outdoor and exhaust air streams. A pump circulates a single phase heat transfer fluid between the coils, transferring sensible heat from the exhaust air stream to the outside air stream in winter and vice-versa in the summer. Glycol is needed because the outdoor air coil is exposed to freezing temperatures and the percentage of glycol depends on the outside design dry bulb. Ethylene glycol is usually used, except propylene glycol is used in food applications; in either event the glycol increases the fluid's viscosity and specific gravity and must be accounted for in the pump selection. The system also needs an expansion tank, a water makeup line, vents at the physical high points and drains at the physical low points. The three-way valve a) modulates to control the heat pulled from the exhaust coil to prevent freezing on the exhaust coil, and b) in some applications may be used to limit the supply air temperature. The pump is turned off during economizer mode, controlled by either OA dry bulb temperature or enthalpy. Like the heat pipe, the runaround loop only transfers sensible energy.

With experienced engineering, both the heat pipe system and coil runaround loops are able to achieve Effectiveness ratings over 65%. However, rather than trying to maximize the Effectiveness per se, this article was initially more interested in maximizing the runaround loop's RER and LCC savings, given a fair physical comparison for both technologies. The 'fair' comparison was not a given because each technology used different fin/tube spacing and patterns. Commonly available computer selection programs were used to determine the technical performance of both technologies for the examples used in Figures 6 and 8, and dozens of computer runs were made for the runaround loop. In the end, two approaches were used to optimize the runaround loop:

[4] Per ASHRAE Fundamentals Handbook, Chapter 44

1. Within the physical parameters of the examples, strive for maximum Effectiveness. I quickly reached ten rows of coil for each side, and going deeper than that would present coil cleaning problems for the owner. And while the airside pressure drop was very high, the pump selection was only a moderate 1.8 BHP. The first row of Figure 12 is the result.
2. Again within the physical parameters of the examples, strive for maximum Efficiency by equalizing the airside pressure drops to the heat pipes; reducing their pressure drops further would not be fair to the heat pipes because, after all, their pressure drops could also be reduced further. The second row of Figure 12 is the result.

MBH Transferred[a]	% Effectiveness[a]	Airside PD " (each)[a]	Tube side PD' (each)/GPM[a]	RER[a]	Capital Cost $000[b]	Annual Maintenance Cost $000[b]	Annual Energy Saved $000[b]	Twenty Year LCC (Savings) $000[b]
252[1]	45	1.40/1.44	32.3/42.8	11.0	45	1.6	4	-4
191[2]	34	.56/.58	17.6/72.9	14.3	44	1.6	7	+35

a. Determined with 1% Design DB/MCWB
b. Determined with BIN data

Figure 12

We find that, indeed, maximizing and using only the Effectiveness to measure results can lead to a poor conclusion. In this case, the negative $4,000 LCC Savings means that the discounted annual energy savings are less than the capital cost and the discounted maintenance costs. On the other hand, maximizing RER (within the constraints of the example) leads to a better conclusion.

Now, with the optimum runaround coil selection in hand, we can compare the heat pipes to it. In Figures 13, 14 and 15, compare the runaround coil only to the two right-hand heat pipe selection; only these three are for applications where the OA and EA ducts are separated. Regarding the heat transfer, it's not unexpected that the heat pipe is superior. That's because the basic principle of the heat pipe is that a two phase medium is used for heat transfer, while the runaround loop relies on a single phase water/glycol solution. The latent heats of vaporization and condensation cause the high heat transfer rates as the two phase medium changes state.

While the runaround coil does have a lower capital cost, we see that its lower Recovery Efficiency Ratio drops it far behind on a LCC analysis. The engineer who designs a runaround coil into a simple heat recovery application where the OA and EA ducts are less than 100 ft. apart, or the contractor who installs it, is allowing a short term benefit while greatly penalizing the owner in the long run.

However, there are still two cases where the runaround coil is preferred:

1. When the distance between the OA and EA coils are beyond 100 ft. In fact, the coils can be located as far apart until the maintenance and airside pressure drop added to the pump's energy makes the project no longer economical.
2. When multiple coils are used at the exhaust and/or outside air locations.

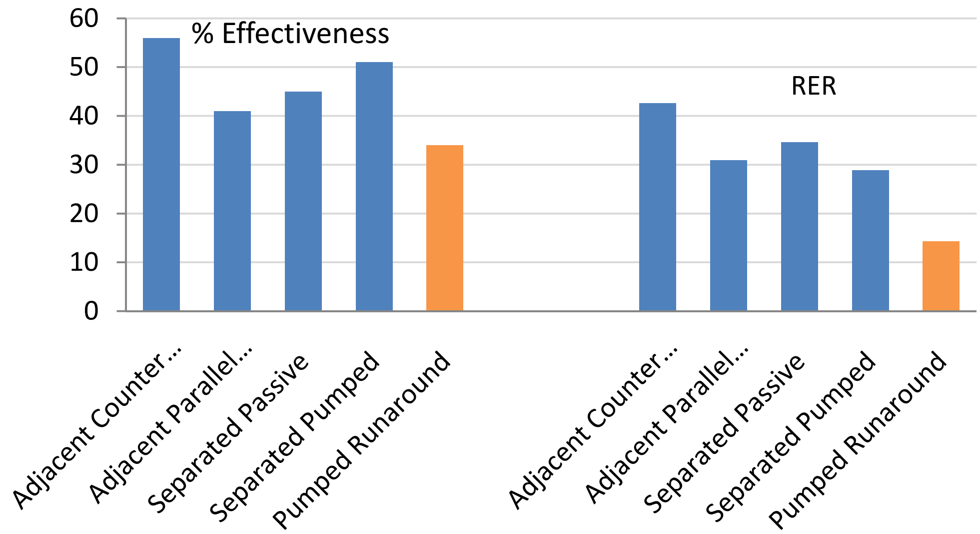


Figure 13

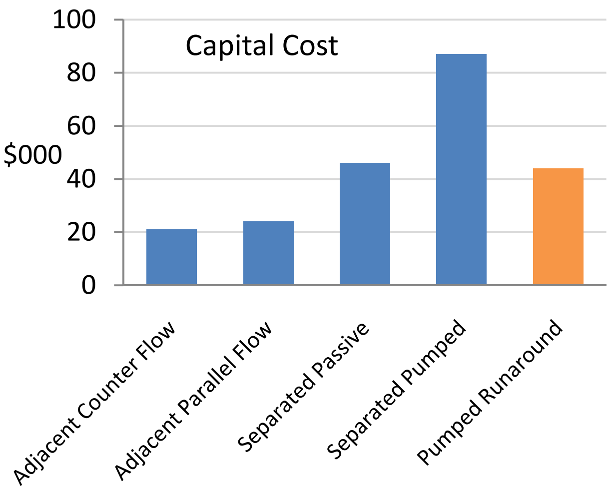


Figure 14

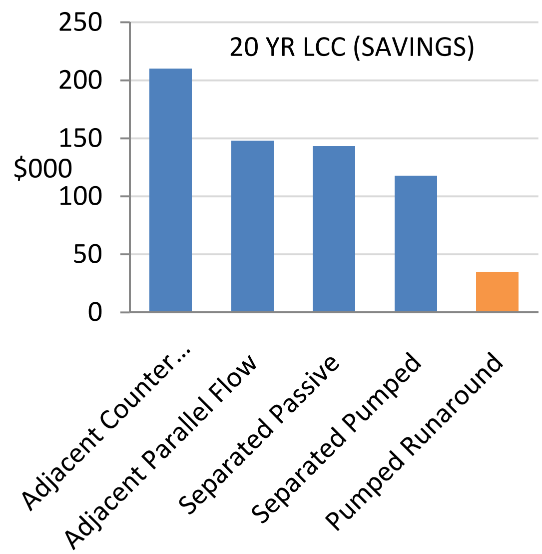


Figure 15

SUMMARY

Innovation, experience and passing the crucible of economics adds these four new/updated models into Today's Paradigm for Air-to-Air Heat Recovery:

1. The Recovery Efficiency Ratio should be used as part of the evaluation criteria of all Air-to-Air Heat Exchangers.
2. In addition to the traditional adjacent, counter flow heat pipe, the HVAC system designer now also has access to adjacent, parallel flow and separated heat pipes. These allow all the benefits from the use of the simple heat pipes to accrue to the owner.
3. Heat pipes should selectively replace enthalpic energy exchangers. Where there isn't a demonstrated need for latent exchange, the simpler heat pipe provides powerful benefits to building owners.
4. Whenever the exhaust and outside air ducts are within 100 ft., heat pipes should replace runaround loops (excluding multiple coil applications).

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APPENDIX

Design Criteria for Figure 6

1. 10,000 CFM of Outside Air at 20.0 ºF DB/18.3 ºF WB; 10,000 CFM of Exhaust Air at 72.0 ºF DB/55.8 ºF WB
2. 500 FPM face velocity on both 6Row/12 FPI heat pipes with R410A (R134A in the pumped system)
3. The split and pumped heat pipes are separated by 50 ft. and one is 10 ft, above the other.

Design Criteria for Figure 8

1. Includes items 1 and 2 above except Chicago BIN data used
2. The 8,760 annual BIN hours include the effects of frost and full and modulating economizer control
3. Utility costs per http://www.northwesternenergy.com/ourcustomers/shared/ratecompare.aspx for medium size commercial business; $.104 KWh, $1.28/therm
4. Life Cycle Capital Cost factors are from "Energy Price Indices and Discount factors for Life-Cycle Cost Analysis" by the National Institute of Standards and Technology, NISTIR 85-3273-26, September 2011, Sponsored by the Department of Energy: DOE discount rate (excluding general price inflation) is 3.0%; Nominal rate (including general price inflation) is 3.9%; implied long-term average rate of inflation is .9%.
5. Central station total cooling plant efficiency, including chiller/condenser pumps and Tower/AHU motors is .75 kW/ton; heating plant efficiency is 70%; fan motor, fan and pump efficiencies are 90%, 70% and 70% respectively; specific gravity of 40% EG solution is 1.07.
6. The separated heat pipes and coil runaround loop are located 40 ft apart horizontally with one device located 10 ft above the other. The runaround loop's equivalent head also includes 35' for the coils and 20' for the valve.
7. Capital costs include:
   a. equipment pricing from Heat Pipe Technology as of Feb, 2012 with appropriate channel markups to the owner
   b. ten man-days at $75/hr burdened for installation of the adjacent heat pipes, and sixteen man-days for the split heat pipes
   c. $2K in materials for the adjacent heat pipes and $3K in materials for the split heat pipes
   d. Twenty per cent markup/profit for the installer
8. Maintenance costs include $1K for replacement filters and four man-hours at $75/hr.