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Development of a Smart Modular Heat Recovery Unit Adaptable into a Ventilated Façade

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Abstract

This paper presents the designing aspects and first experimental characterization of an adaptable Smart Modular Heat Recovery Unit (SMHRU) developed under the scope of the E2VENT Project. This SMHRU is being designed as a part of an adaptable renovation module for the retrofitting of multi-storey residential building from the *60*'s, *70*'s across Europe that embeds the SMHRU and an energy storage system based on a phase change material. This heat recovery unit will be adjustable to be integrated into the ventilated façade cavity, and able to recover heat from ventilation air, preheating the ventilation air in winter and precooling it in summer. This will allow an efficient combination of consumption reduction and acceptable air indoor quality.
The first part of the paper presents designing considerations and thermal stationary analysis of the heat recovery unit, which is based on experimental correlations obtained for air-to-air compact offset-strip-fin plate heat exchangers. Secondly CFD analysis of the distributor of the SMHRU is presented. Finally prototype first performance estimation based on experimental results is presented.

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Keywords: Air-recovery; Air-quality; Compact-heat-exchangers; Offset-strip-fin-plates; Ventilated-façade; CFD Analysis.

1. Introduction

The air renewal ensures the indoor air quality and prevents the occupants from health issue. In the case of existing buildings, the low air tightness allows natural ventilation through the façades, but when the building is retrofitted,

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Nomenclature		**Subscripts**	
COP	Coefficient of performance	in	inlet
ε	efficiency	c	cold
EES	Engineering Equation Solver	h	hot
f	friction factor	in	inlet
j	Colburn j-factor	out	outlet
NTU	Number of transfer units		
OFS	Offset Strip fins		
p	pressure		
SMHRU	Smart Modular Heat Recovery Unit		
T	Temperature		
v	velocity		

the thermal losses through the façade are limited by adding a layer of insulation (either internal or external), and the windows are classically changed in order to have a more efficient glazing. Those aspects of the renovation have impact on the air tightness of the building and the leaks through the façades are highly limited and thus the air tightness is higher, making the natural air renewal lower and therefore the indoor air quality can be drastically reduced.

E2VENT Project develops an adaptable Smart Modular Heat Recovery Unit (SMHRU) which is combined with a system based on phase change material energy storage system. This heat recovery unit will be adjustable to work into the ventilated façade cavity, and able to recover heat from ventilation air, preheating the ventilation air in winter and precooling it in summer. This will allow an efficient combination of consumption reduction and acceptable indoor air quality.

2. SMHRU Design

Heat recovery or air-to-air heat recovery systems are made in so a lot of different types, sizes, configurations and flow arrangements. Most common types of heat recovery units are: fixed-plate, heat-pipes, thermal wheel and round around systems. The SMHRU must fit within the E2VENT module, and thus must be placed between the wall and the cladding. Consequently fixed plate heat exchangers as they are thinner are the most favourable type of heat exchangers. Plate fin heat exchanger are characterized by high effectiveness, compactness, low weight and moderate cost.

Offset strip fin (OSF) plates have been considered for the SMHRU design. OSF are widely used to enhance fin geometries in large variety of industrial processes. This is because they are considered as one of the best heat transfer geometries' relatively to friction factor; and large analytical, numerical and experimental investigations have been performed over the last *50* years. Main characteristics of the plates selected are described below together with the scheme (see Fig. 1):

Fin type: *1/8* Lanced OSF
Lanced length: *3.175* mm.
Material: Aluminium *3003*.

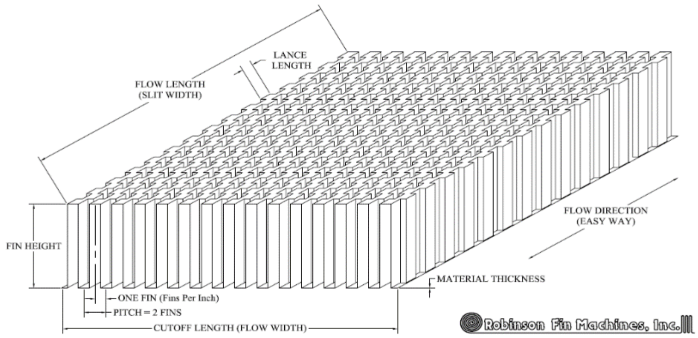


Fig. 1. OFS Plates scheme and terminology. http://www.robfin.com/

Overall fin dimensions:
Material thickness: *0.304* mm.
Fin height: *12.49* mm.
Fins per inch: *8*.

Overall plates dimensions:
Flow length: *250* mm.
Cut off: *350* mm.

Empirical correlations for different extended surfaces are summarized in the bibliography, including OSF plates. Recommended correlations for obtaining j-Colburn and friction factors are those obtained by Joshi and Webb[1] (*1987*) and Manglic and Bergles[2] (*1990*). The last ones employed an asymptotic combination of individual correlations for the laminar and turbulent flow regimes, but for estimation purposes the following simplified correlations can be used for OSF surfaces with high fin area/total area ratio and with thin fins[3]. Fig. 2 shows comparison of the correlations provided in equations (1) and (2) and experimental data performed by Kays and London[4] for plates *3/32-12.22*, used as comparing reference as having most similar plate height (*12.30* mm) to those selected from ROBINSON catalogue.

$$j = 0.6 \cdot \mathrm{Re}_l^{-0.5} \tag{1}$$

$$f = 4 \cdot j \tag{2}$$

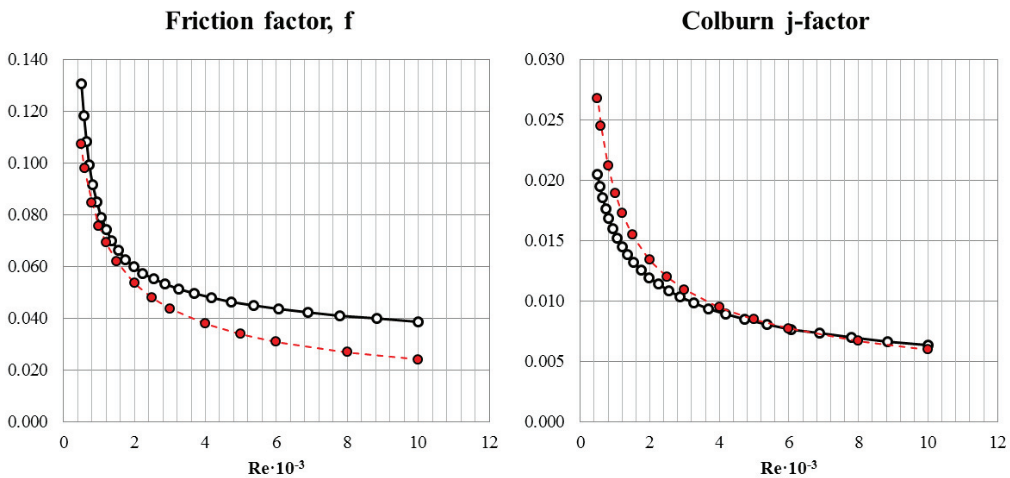


Fig. 2. Comparison between Colburn-j and friction factors obtained by correlation described in equations (1) and (2) (red lines and circles) and experimental values obtained by Kays and London4 (black lines – white circles) for plate *3/32-12.22*.

The assumptions adopted for the modelling the heat transfers that take place in the SMHRU are the following:

- The working condition is steady state which means the variations of operating conditions are not to be considered.
- The fouling factor, i.e. additional heat transfer resistance due to dirt accumulation, is not considered in thermal modelling since conventionally it is negligible in gas-to-gas applications.
- The heat transfer coefficient is supposed to be uniform throughout the heat exchanger.

Simulation results in Fig. 3 show that efficiency increases with the length of the proposed two countercurrent plate. SMHRU achieves an efficiency between *70* and *87%* for *500* and *1.500* mm length when nominal *45* $m^3.h^{-1}$ volume flow rate is considered. For *1.000* mm length, corresponding to 4 commercial plates, an efficiency over *80%*

is achieved. *1.000* mm supposes almost *5* number transfer unit heat exchanger and according to Fig. 3, increasing the heat transfer area would not lead to a notable efficiency rise. This heat exchanger would obtain a *289* W heat exchange when a *20 K* temperature gradient is supposed between inside and outside of the dwelling.

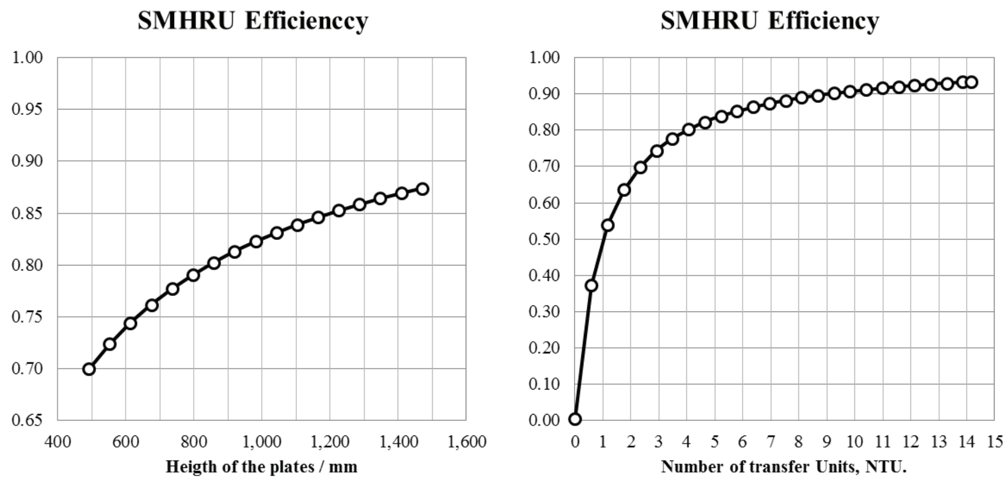


Fig. 3. SMHRU efficiency depending on length of the SMHRU in mm. Efficiency compared to number of transfer units NTU.

Apart from the correlations implemented in the EES[5] model, THERM[6] Software has been used in order to compare heat transfer coefficients obtained and ideal ones obtained by 2D dimensional conduction heat transfer analysis, based on the finite-element-method. From results, one can conclude that, although U-values of the projected surface obtained by THERM are higher than those obtained by EES model, values obtained by EES model could be considered correct for thermal dimensioning of the SMHRU. Comparison of those values obtained by EES and THERM are presented in Fig. 4. The increase of the values could be explained as THERM calculation are based in an ideal performance case, where convective heat transfer values are considered uniform in whole boundaries, since correlations are based in real experimental studies performed, where real air flow and heat transfer performs' uncertainties are also "included". Besides, having lower values results in a conservative calculation, this is always desired in order to ensure SMHRU's performance.

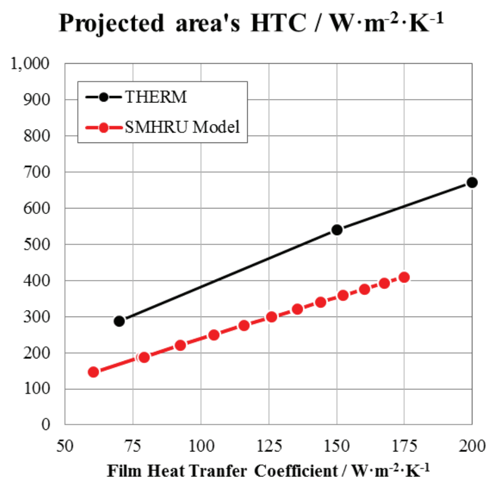


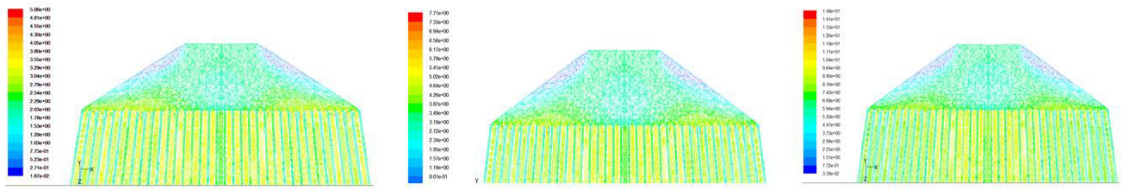
Fig. 4. Comparison between heat transfer coefficients of the projected area obtained by correlations and THERM Simulation tool

3. Distributor system

One of the assumptions adopted for the SMHRU modelling was that the flow rate and consequently uniform heat transfer coefficients were supposed to be uniform throughout the heat exchanger. In order to study the performance of the designed distributor a CFD analysis was performed using Ansys Fluent 16[7]. The objective is to study the airflow distribution in the current header of the heat exchanger. The following main assumptions are used for the model solution:

- It is assumed that the flow is uniformly distributed at the entry of the distributor.
- Constant velocity boundary is supposed at the inlets of the distributor.
- No velocity is supposed at the distributor walls.
- Outlet pressure boundary is supposed at the SMHRU outlets.

From the results, it appears that there is an important air flow jet at the entry of the distributor and an air recirculation at the entry of the distributor creating an air maldistribution in the plates, consequently the air flow within central plates is higher, although all the channels are served by the inlet airflow. Fig. 5 shows the velocity contours for different air flows (design airflow rates: *30*, *45* and *85* $m^3 \cdot h^{-1}$) and the air recirculation at the entry of the distributor.



30 m^3/h 45 m^3/h 85 m^3/h

Fig. 5. Reversed flows at the entrance of the distributor (velocity field in $m \cdot s^{-1}$).

Although all the channels are served by the inlet airflow and the OSF plates would uniform flow rate throughout the heat exchanger, a solution to improve the air distribution has been analysed. Effect of increasing the height of the distributor from *100* mm to *200* mm and consequently decreasing the air flow rate angle of attack from *51.34º* to *32.00º* has been studied (see Fig. 6). The decrease of this angle permits to shift the impact of the inlet air jet and with the new geometry the mentioned air recirculation zone is decreased and the air distribution is more uniform. Fig. 7 presents both different heights distributors' performance for nominal *45* $m^3 \cdot h^{-1}$ flow. Results showed that higher distributor height, i.e. lower angle of attack, supposes a lower range of the pressures at the SMHRU plate's inlet and the air is more uniformly divided, lowering the impact of the air jet at the inlet and thus taking advantage of greater heat transfer area in the SMHRU.

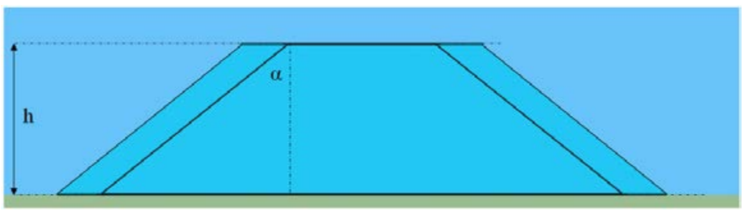


Fig. 6. Distributor height h, and angle of attack α definition.

A hypothetical performance of a SMHRU with straight heat exchange plates and not OFS has been modelled for quantifying the well distributor design by CFD analysis. If straight plates were installed airflow would not get more uniform due to the fact that air cannot flow from one channel to another. This analysis showed that the efficiency of the SMHRU is increased by more than *100%* when the distributor height is increased, from *45%* to *95%*.

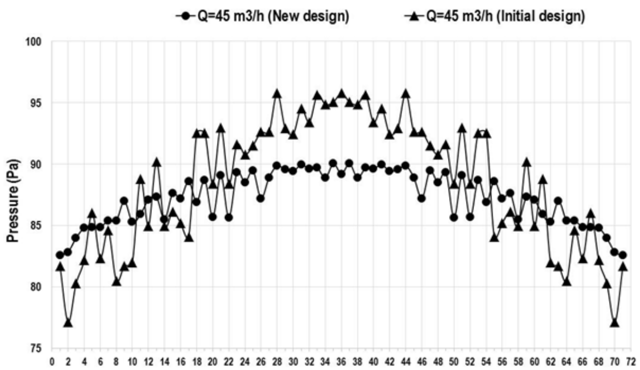


Fig. 7. Pressure profile at the inlet of the SMHRU's plates for initial design h=0.1 m and New design h=0.2 m. 45 m3·h-1.

4. Experimental setup

The test facility built-up operates in continuous mode in which SMHRU is tested fed by desired temperature and flow rate conditions. It consists of two climatic chambers where inlet temperature requirements are obtained by resistances as electrical heaters in the case of hot circuit and an air conditioning system has been installed in the cold circuit of the SMHRU. Temperatures of *50ºC* and *-10ºC* can be obtained for hot and cold circuits respectively. Two ventilators have been installed inside each climatic chamber in order to get homogeneous air temperatures.

The air streams going into the SMHRU are driven by two centrifugal fans installed directly in the distributors which power can be controlled with a potentiometer from *0* to *10*, supplying between *12* and *24V* and allowing to have different air flow rates.

The measured parameters in order to characterize the SMHRU performance are:

- Inlet and outlet temperatures of heat and cold flow rates ($T_{h,in}$, $T_{h,out}$, $T_{c,in}$, $T_{c,out}$).
- Velocities in the circuits for calculating flow rate (v_h, v_c).
- Differential pressure between ventilator inlet and SMHRU outlet (Δp_h, Δp_c).
- Fan's consumption capacities (P_h, P_c).
- 15 thermocouples have been installed in each side SMHRU surfaces in order to characterize the temperature profiles of the plates. This information will help understanding the distribution of the flow and the heat in the different parts of the SMHRU air distribution and heat transfer occurring in various area of the SMHRU w

5. First results and discussion

The first *5* different tests are presented in this paper, in which a sensitivity study of the air flow rate effect at *15 K* temperature gradients on the SMHRU are analysed. The flow rates analysed in these first tests are around *5*, *10*, *15*, *20* and *25* $m^3.h^{-1}$.

The following equations and parameters are used to assess the SMHRU performance parameters considered in the present work. The SMHRU efficiency is calculated from temperature difference between inlet and outlet of one of the streams and the maximum temperature difference. When equal supply and exhaust mass flow rates are set, the overall efficiency can be calculated using equation (3):

$$\varepsilon = \frac{T_{h,in} - T_{c,out}}{T_{h,in} - T_{c,in}} = \frac{T_{c,out} - T_{c,in}}{T_{h,in} - T_{c,in}} \tag{3}$$

The heat transfer capacity in the SMHRU can be calculated taking into account mass flow rates entering in each circuit and inlet and outlet temperatures. Table below resumes test conditions and also results, i.e. outlet temperatures, efficiencies and capacities for hot and cold streams, obtained from measurements.

Table 1: Test conditions (inlet temperatures and flow rates) and SMHRU performance parameters.

	$T_{h,in}$	q_h	$T_{c,in}$	q_c	ΔT_{max}	$T_{h,out}$	$T_{c,out}$	ε_h	ε_c	Q_h	Q_c
	ºC	$m^3 \cdot h^{-1}$	ºC	$m^3 \cdot h^{-1}$	K	ºC	ºC	%	%	W	W
Test 1	*30.38*	*4.98*	*16.94*	*4.91*	*13.44*	*21.17*	*27.45*	*68.55*	*78.16*	*16.56*	*18.63*
Test 2	*30.07*	*9.93*	*15.77*	*9.85*	*14.30*	*20.58*	*28.20*	*66.46*	*86.89*	*34.06*	*44.20*
Test 3	*30.96*	*15.08*	*15.48*	*15.04*	*15.49*	*20.45*	*27.93*	*67.91*	*80.48*	*57.23*	*67.69*
Test 4	*30.13*	*20.22*	*15.24*	*20.26*	*14.90*	*20.99*	*27.77*	*61.44*	*61.44*	*66.72*	*91.76*
Test 5	*29.35*	*22.78*	*15.23*	*22.71*	*14.12*	*21.21*	*27.16*	*57.66*	*57.66*	*66.89*	*97.86*

These first tests showed that increasing the input flow rate decreases the overall SMHRU's efficiency eventhough it still maintains acceptable air distribution. Heat transfer capacities increased from *16.56* to *66.89* W, in the case hot stream is analysed, and from *18.63* to *97.86 W* for the cold one. An increase of the flow rate of *357%* leads to an increase of *300%* of the heat transferred by the hot stream, which is in agreement with lower distribution performance, but in the case of the cold stream the heat transfer is increased by *425%*. Temperatures registered in the thermocouples have been analysed in order to explain this effect.

The thermocouples positioned at *100, 300, 500, 700* and *900* mm in both parts of the SMHRU showed a linear temperature increase along the SMHRU. These values have been used in order to estimate temperatures just entering and leaving the heat exchange part. While the deviation from these temperatures and registered ones in the test bench are lower than *1%* for the hot-in, hot-out and cold-out streams, the deviation of the cold stream entering the SMHRU is between *16* and *20%*. These calculations showed the cold stream is previously heated by the fan that ensures the air circulation. Cold air is heated by approximately *6.21, 10.30, 14.12, 20.30* and *23.41* W for corresponding flow rates showed in Table 1, explaining the differences between efficiencies and capacities from cold and hot streams presented on it.

Finally the model used for dimensioning the first SMHRU prototype has been compared with the first experimental results. The model does not take into account the effect of the fan explained in the previous paragraph so the estimated temperatures entering and leaving the core part of the SMHRU have been used as input, as well as flow rates measured during tests. Results, resumed in **Error! Reference source not found.**, showed, as explained before, that the efficiency decreased when air flow rate is increased, but a greater volume of air is heated (or cooled) and thus the capacity increases. As the air flow rate is increased, the prototype performance is lower than the one predicted by the models. Model and prototype performances show a deviation from around *3* to *17%* when mass flow rates are increased. When mass flow rates are increased, distributor CFD analysis showed that the effect of the air jet is bigger, reducing the heat transfer effective area.

6. Conclusions

Designing considerations for the conception of a heat exchanger adapted to be installed in the cavity of ventilated facades were presented in this paper. It is explained why OFS plates geometries is considered the best option in order to achieve the objectives of the project. A thermodynamic model implemented in EES has been developed for first prototypes definition. Then a more detailed analysis corresponding to the distributor design and CFD performance analysis was presented and results discussed.

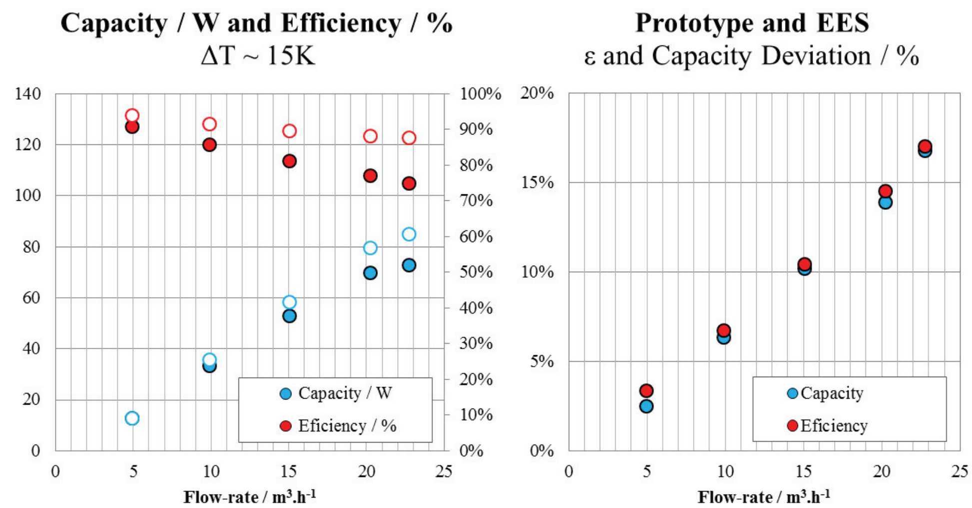


Fig. 8. Capacity and Efficiency of the SMHRU for different flow rates. Prototype performance and EES model comparison.

The first experimental results showed that the performance obtained based on measurements on the prototypes is in agreement with the calculated performance obtained with the model, and SMHRU is in experimental phase and results cannot be considered as definitive ones, it seems to be a promising solution to achieve energy efficiency in buildings with ventilated façades. The measured prototype performance is reduced as the mass flow rate is increased because of the impact of the correlated worse air distribution and higher inlet jet, as shown in the distributor CFD analysis. Finally, a large influence of the fan performance in the global SMHRU performance has been identified. The temperature of the cold air entering the SMHRU is increased by *20%*, which results in a different SMHRU performance. This effect needs to be deeply quantified and considered into the models for redesign of the SMHRU.

Acknowledgements

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