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Polymeric materials in solar-thermal systems - performance requirements and loads

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Abstract

A major basic problem in selecting appropriate polymeric materials and processing technology routes is related to the lack of well-defined functional and performance requirements on the component level and to material property requirements on the specimen level.

Hence, in a first step several reference climate regions were defined for pumped systems (continental (Graz/Austria), moderate climate (Beijing/China)) and non-pumped systems (Mediterranean (Athens/Greece), hot and dry (Pretoria/South Africa), hot and humid (Fortaleza/Brazil)), respectively. For each of these reference regions various solar-thermal plant types (e.g., domestic hot-water systems for single family houses (pumped and thermosiphon); domestic hot-water systems for multi-family houses; solar combi-systems for domestic hot-water and space heating (pumped) were pre-defined and evaluated and optimized virtually by modelling and simulation.

To determine performance requirements on the component level and to derive material property requirements on the specimen level all-purpose modelling and design tools for collectors were implemented and used which allow for the description of temperature profiles, stagnation conditions, efficiency curves, pressure losses, distribution of fluid and heat flow and the thermal and hydraulic optimisation of the whole collector.

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Keywords: performance requirements; flat-plate collector; polymer; overheating protection

1. Introduction

A crucial aspect of using polymeric materials in solar thermal systems is the exact knowledge about the occurring loads especially for temperature and pressure changes. The limited thermal property in various polymers in comparison to the present primarily used materials (copper, aluminum or glass) in reference systems makes it

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inevitable to determine load profiles. In the framework of the Austrian project SolPol investigations were made to create temperature and pressure load matrices for the main components of solar thermal systems. To achieve a broad knowledge-base, different applications (domestic hot water in single and multifamily houses, combi-systems) and systems concepts for the main climate zones of the world have been investigated. Furthermore, modified polymeric solar thermal systems with overheat protection (backcooling, ventilation, thermotropic layer) and without overheat protection (drain-back, thermosiphon) have been examined. Extended simulations have formed the basis to deliver load profiles for solar thermal systems based on polymeric materials. This paper gives an overview over the performance requirements for the materials.

2. Reference sites and applications

Five reference sites with existing potential and intensified solar thermal market activities have been identified to generate a wide range of system loads as a result of different climate conditions: continental, mediterranean, hot and dry, tropical and moderate. The dimensioning of the reference systems was determined by the collector area which is in line with the specific market standards and the climate conditions (see Table 1).

Table 1. Summary of the climatic conditions at the selected locations; applications as well as the dimensions of the reference solar thermal systems (gross collector area) correspond to the chosen site; DHW…domestic hot water, SFH…single-family house, MFH…multi-family house.

	climatic conditions			gross collector area [m²]			
site / climatic zone	accumulated global radiation (horizontal) [kWh/m²a]	ambient temperature min [°C]	ambient temperature max [°C]	DHW-SFH, pumped	DHW-SFH, thermo siphon	Combi-System-SFH, pumped	DHW-MFH, pumped
Central Europe (Graz) / continental	1160	-12	33	6,6	-	18	44
South Europe (Athen) / mediterranean	1610	2	38	-	3,8	17	42
Africa (Pretoria) / hot, dry	2050	1	34	-	2,5	-	38
Brazil (Fortaleza) / tropical	2030	22	33	-	2,4	-	22
China (Peking) / moderate	1480	-14	38	-	4	18	50

3. Thermal loads in an overall system

Determination of load profiles prerequisites an overall consideration of the whole solar thermal system. For this purpose the reference systems were built up and simulated with the simulation programs Polysun [5] and SHW [2]. Figure 1 shows the temperature load profiles from different system components derived from a typical reference system in Graz (Austria) as a representative location in Central Europe. The solar thermal system provides domestic hot water and supports space heating. The temperature in the energy storage tank is limited to a maximum value of about 90 °C by the controller.

Especially during summer month, temperatures above 200 °C can be reached at the surface of a selective coated absorber in the state of system stagnation. This implies that several technological challenges have to be met prior to the use of polymeric materials in solar thermal systems. This includes active overheat protection (backcooling, ventilation, thermotropic switching) and passive overheat protection (thermosiphon systems) for commodity plastics as well as “drain-back” solutions for engineering and high performance polymers.

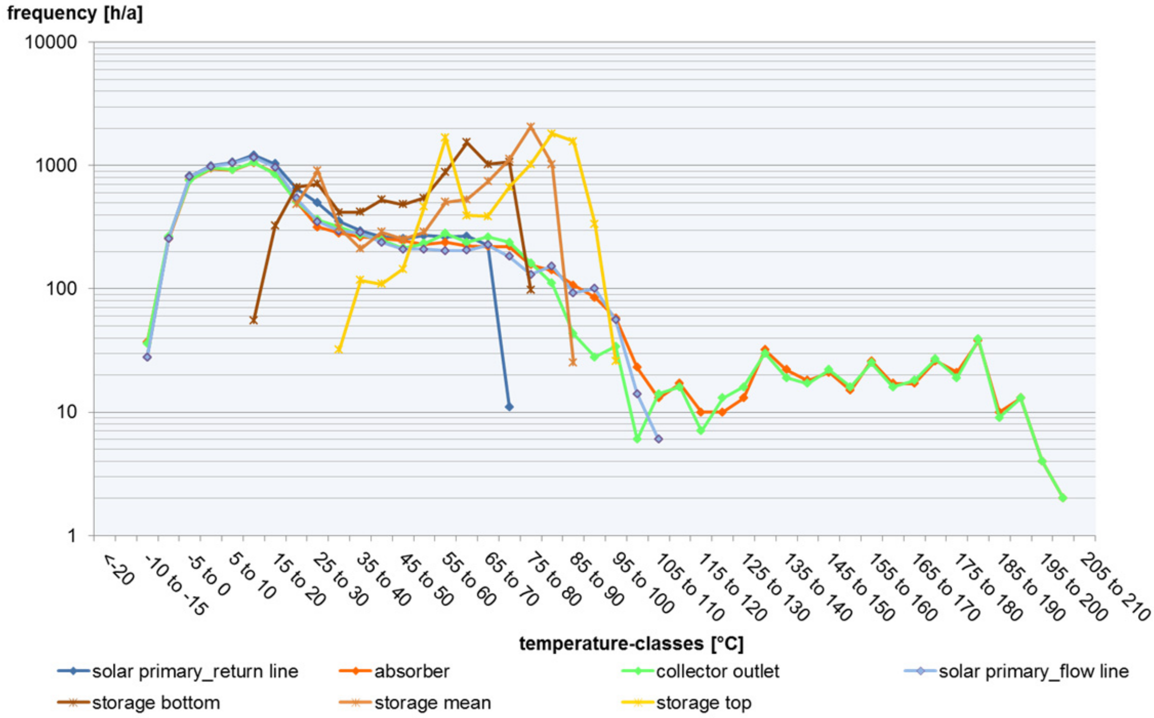

Fig. 1. Frequency (log scale) of the occurring thermal loads on different system components; reference combi-systems single family houses in Central Europe (Graz) with selective metal absorber.

4. Thermal stress in solar thermal collectors with and without overheating protection

Solar thermal systems that reach the stagnation state will overheat, resulting in high temperature and pressure loads for the collector and the surrounding components. Depending on how well it succeeds limiting these loads, without reducing the efficiency in normal operation, determines whether high performance polymers or low-cost engineering or commodity plastics can be used.

In the case of collectors based on polymeric materials with overheating protection (OHP), the thermal loads will be reduced by a controlled increase of the heat- or optical losses by either backcooling, ventilation, thermotropic switching or in the case of thermosiphon systems by hydraulic circuits that are open to the atmosphere. All these methods should keep the collector temperature below the critical temperature of about 95 °C (max. 100 °C) during stagnation. In the other case a drain-back system provides for the automatic emptying of the collector and piping when the system is turned off. The circulation pump shuts itself down and the water drains by gravity to the drain-back tank which can be open to the atmosphere. By means of such drain-back systems collector overheating can´t be avoided but the correlated pressure loads are reduced or waived entirely.

Figure 2 depicts the collector efficiency curve (solar irradiation 1000 W/m²; ambient temperature 30 °C) of the polymeric collectors with and without OHP. Ideally, the temperatures may be limited by the OHP to 85 ° C during stagnation, without OHP temperatures occur 160 ° C.

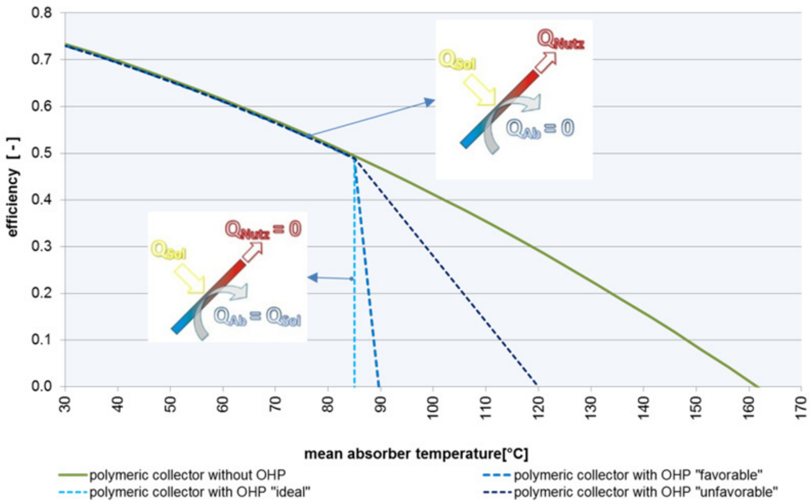

Fig. 2. Collector efficiency curves of the polymeric collector without OHP (green) and different efficient OHP for the polymeric collector (blue).

Figure 3 depicts the simulated mean absorber temperature frequency of reference systems and solar thermal systems based on polymeric materials with OHP (backcooling) and without OHP (drain-back) for a single-family house in Central Europe by varying applications. In the reference system the maximum achieved temperatures during stagnation reaches 195 °C. The temperature in the drain-back systems reached a maximum level of 165 °C due to the nonselective coated polymeric absorber. The systems with an active OHP are limited to 90 °C.

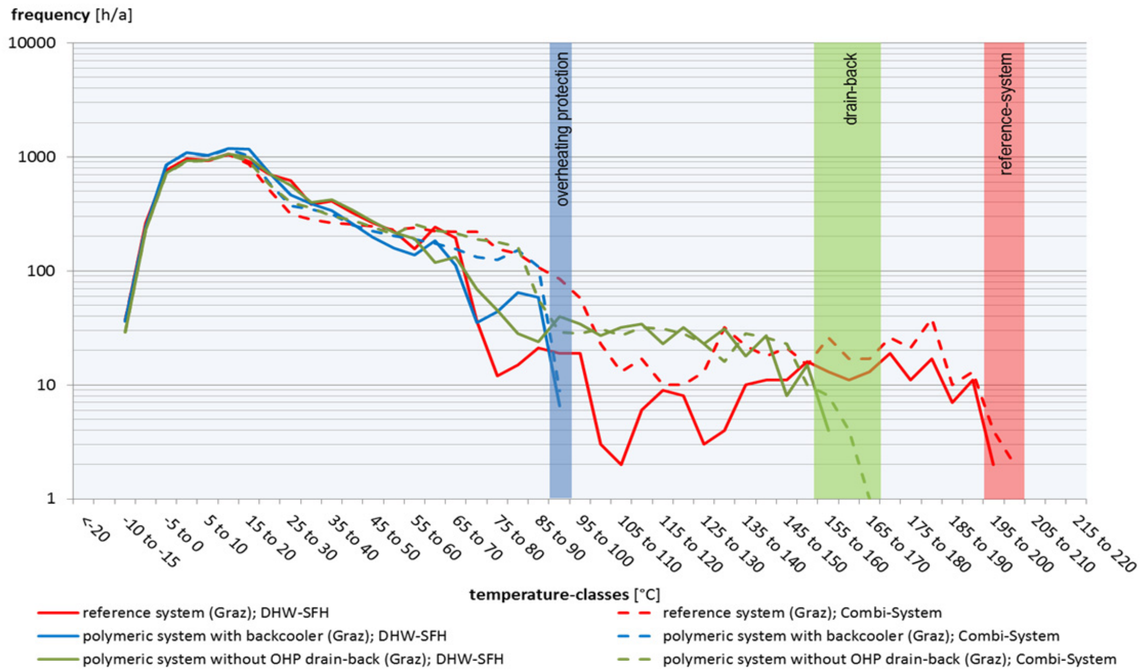

Fig. 3. Frequency (log scale) of the mean absorber temperatures of polymeric collectors with OHP (backcooler; blue), without OHP (drain-back; green), and the reference collector (red) in varying applications (domestic hot water; combi systems) for single family houses.

Figure 4 represents a cross-section of the mean absorber temperature frequency per year through the simulated polymeric systems with and without OHP for different applications and system concepts in various locations. It is made clear in this regard that the lower limit of the temperature profile is mainly determined by climate conditions, whereas the upper limit additionally depends on the collector properties and concepts as well as on the heat demand. The maximum temperature in thermosiphon systems is limited to system design and due to the fact of an inherent mains water supply and of course the user behavior (hot water tap profiles).

The performance requirements (thermal-pressure stress) for the reference and polymeric systems are summarized and displayed in a convenient matrix format (see Table 2)

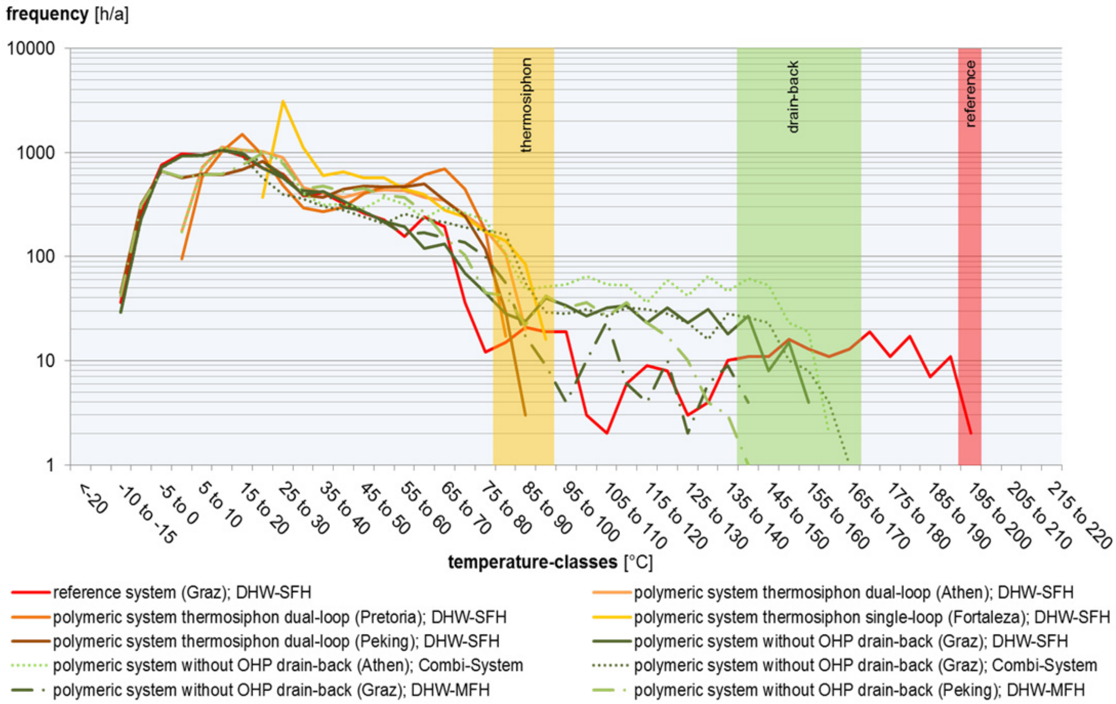

Fig. 4. Frequency (log scale) of the mean absorber temperatures of polymeric collectors with OHP (thermosiphon; yellow), without OHP (drain-back; green), and the reference collector (red) in varying climate zones and applications (domestic hot water; combi-systems) for single- and multifamily houses.

5. Maximum temperature loads of different collector components

To determine the thermal load on the collector components (absorber, insulation, cover, etc.) for one calendar year (hourly values) a special, one-dimensional collector model working substantially on the basis of the methods and models described in [2] and [3] was created, which allows calculation of the collector components. Furthermore, this calculation approach also allows the determination of the component temperatures in the case of maximum exposure to an unfilled system, i.e. the panels have been mounted, but are not filled. The developed calculation method used on the one hand site specific climate data and on the other hand the temperatures occurring in the operating state of the heat transfer medium to determine the temperatures occurring on the collector components (absorber, insulation, cover). Figure 5 shows exemplary results for the temperature load of the components for the defined polymeric collector at the locations Graz and Fortaleza.

Due to high radiation values and high average outdoor temperatures at the site Fortaleza (tropical climate), the temperature loads in an unfilled collector system are significant higher in direct comparison to the continental climate in Central Europe.

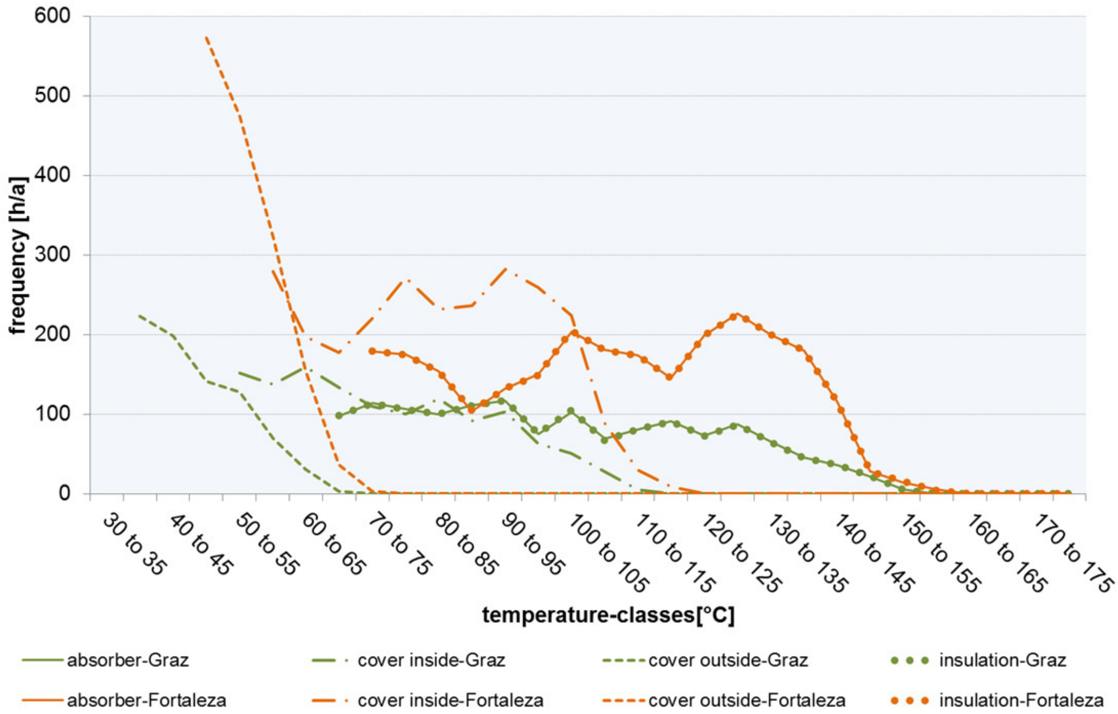

Fig. 5. Annual frequencies of temperature stress of different components in plastic panels (plastic cover, plastic absorbers, insulation) in the unfilled system state (maximum load) for the locations Graz and Fortaleza. Only irradiation values greater than 300 W / m² were taken into account.

6. Pressure stress in solar thermal collectors with and without overheating protection

Conventional system procedures during stagnation are well understood and measures to handle this state are known. Nevertheless for economically priced polymer collectors stagnation will be a considerable challenge caused by the high temperature and pressure stress during standstill times of the solar system. In closed systems the pressure development is directly related to the temperature development. Therefore measures to overcome this disadvantage have already been mentioned above. Open drain-back systems offer the ability to reduce the pressure stress.

Figure 4 depicts the frequency of the calculated pressure stress for the reference- and polymeric systems with overheating protection (OHP), with backcooler and without OHP as drain-back solution for the application domestic hot water in single-family houses at five reference sites.

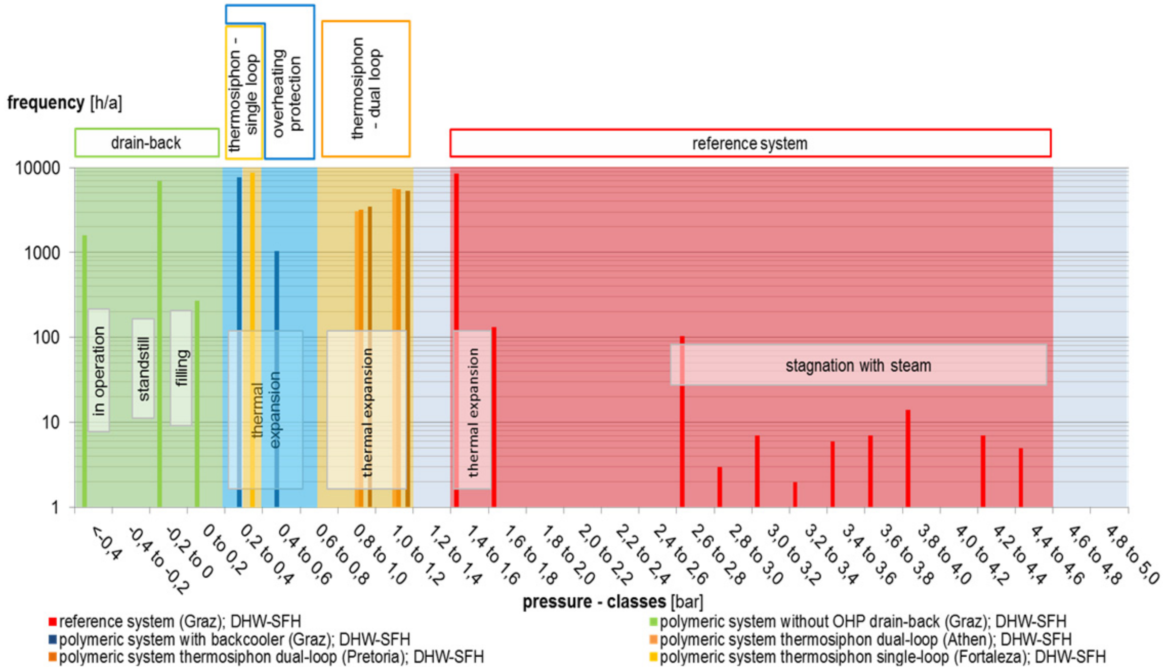

Fig. 6. Frequency of pressure stress of polymeric- and reference absorbers for the application “domestic hot water” in single family houses at various sites (excess pressure).

In the closed systems (red area) the pressure development depends on different facts: temperature, stagnation behavior of the solar loop and the dimension guidelines of the expansion vessel. In systems with active overheating protection (blue area) and dual-loop thermosiphon systems (brown area) evaporation doesn´t take place, so the maximum pressure depends on the thermal expansion of the heat transfer medium. The maximum occurring pressure in atmospheric single-loop thermosiphon systems (yellow area) is corresponding to the geodetic height difference between the storage and the collector. Due to the automatic emptying of the collector and piping in drain-back systems (green area), evaporation can be almost completely avoided. The maximum occurring pressure takes place during the filling process (geodetic height of the collector approx. 2 m). However, during operation there will be a negative pressure caused by the suction effect (geodetic height difference between collector and drain-back tank) of the flow pipe.

7. Pressure and temperature matrix

The following matrix summarizes the temperature- and pressure stress levels of the regarded solar thermal systems. The frequencies of the temperature have been summarized to larger temperature classes. The corresponding values of the pressure are in the same column.

Table 2. Pressure and temperature matrix (more precise data are available on request).

application ↓	temperature classes →	<0 [°C] frequency [h/a]	<0 [°C] pressure min [bar abs.]	<0 [°C] pressure max [bar abs.]	0 to 75 [°C] frequency [h/a]	0 to 75 [°C] pressure min [bar abs.]	0 to 75 [°C] pressure max [bar abs.]	75 to 100 [°C] frequency [h/a]	75 to 100 [°C] pressure min [bar abs.]	75 to 100 [°C] pressure max [bar abs.]	100 to 125 [°C] frequency [h/a]	100 to 125 [°C] pressure min [bar abs.]	100 to 125 [°C] pressure max [bar abs.]
Domestic hot water - SFH	reference system pumped; (Graz)	1059	2.46	2.47	7431	2.47	2.61	86	2.61	2.67	25	2.68	2.74
	polymeric system without OHP; drain-back (Graz)	978	0.60	1.14	7337	0.60	1.14	171	0.60	1.14	148	1.00	1.00
	polymeric system with OHP; backcooler (Graz)	1125	1.27	1.31	7462	1.29	1.51	173	1.49	1.57	0	-	-
	polymeric system thermosiphon; dual-loop (Pretoria)	0	-	-	8564	0.98	1.08	196	1.08	1.09	0	-	-
	polymeric system thermosiphon; single-loop (Fortaleza)	0	-	-	8347	1.40	1.40	413	1.40	1.40	0	-	-
	polymeric system thermosiphon; dual-loop (Peking)	1021	0.97	0.97	7589	0.98	0.98	150	1.08	1.09	0	-	-
	polymeric system thermosiphon; dual-loop (Athen)	0	-	-	8456	0.98	1.08	304	1.08	1.09	0	-	-
Combi system - SFH	reference system pumped; (Graz)	1054	2.68	2.69	6791	2.69	2.76	547	2.76	2.79	73	2.79	2.83
	polymeric system without OHP; drain-back (Graz)	970	0.60	1.14	7047	0.60	1.14	455	0.60	1.14	149	1.00	1.00
	polymeric system with OHP; backcooler (Graz)	1123	1.26	1.29	7243	1.29	1.54	394	1.53	1.61	0	-	-
	polymeric system without OHP; drain-back (Athen)	0	-	-	7697	0.60	1.14	484	0.60	1.14	267	1.00	1.00
Domestic hot water - MFH	polymeric system without OHP; drain-back (Graz)	975	0.60	1.14	7524	0.60	1.14	186	0.60	1.14	54	1.00	1.00
	polymeric system without OHP; drain-back (Peking)	1007	0.60	1.14	7413	0.60	1.14	183	0.60	1.14	139	1.00	1.00

application ↓	temperature classes →	125 to 150 [°C] frequency [h/a]	125 to 150 [°C] pressure min [bar abs.]	125 to 150 [°C] pressure max [bar abs.]	150 to 175 [°C] frequency [h/a]	150 to 175 [°C] pressure min [bar abs.]	150 to 175 [°C] pressure max [bar abs.]	175 to 200 [°C] frequency [h/a]	175 to 200 [°C] pressure min [bar abs.]	175 to 200 [°C] pressure max [bar abs.]	>200 [°C] frequency [h/a]	>200 [°C] pressure min [bar abs.]	>200 [°C] pressure max [bar abs.]
Domestic hot water - SFH	reference system pumped; (Graz)	39	2.74	3.88	72	3.70	4.72	48	3.70	5.45	0	-	-
	polymeric system without OHP; drain-back (Graz)	107	1.00	1.00	19	1.00	1.00	0	-	-	0	-	-
	polymeric system with OHP; backcooler (Graz)	0	-	-	0	-	-	0	-	-	0	-	-
	polymeric system thermosiphon; dual-loop (Pretoria)	0	-	-	0	-	-	0	-	-	0	-	-
	polymeric system thermosiphon; single-loop (Fortaleza)	0	-	-	0	-	-	0	-	-	0	-	-
	polymeric system thermosiphon; dual-loop (Peking)	0	-	-	0	-	-	0	-	-	0	-	-
	polymeric system thermosiphon; dual-loop (Athen)	0	-	-	0	-	-	0	-	-	0	-	-
Combi system - SFH	reference system pumped; (Graz)	106	2.83	4.43	101	4.25	5.40	86	4.25	5.40	2	4.25	4.25
	polymeric system without OHP; drain-back (Graz)	116	1.00	1.00	23	1.00	1.00	0	-	-	0	-	-
	polymeric system with OHP; backcooler (Graz)	0	-	-	0	-	-	0	-	-	0	-	-
	polymeric system without OHP; drain-back (Athen)	268	1.00	1.00	44	1.00	1.00	0	-	-	0	-	-
Domestic hot water - MFH	polymeric system without OHP; drain-back (Graz)	21	1.00	1.00	0	-	-	0	-	-	0	-	-
	polymeric system without OHP; drain-back (Peking)	18	1.00	1.00	0	-	-	0	-	-	0	-	-

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